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13. ABSTRACT *(Maximum 200 words)*

The study of mechanics of sandwich structures and a development of new and innovative structural concepts have been conducted in the course of the effort. In particular, our research was concerned with a development of Sanders'-type theory of cylindrical sandwich shells with different facing operating in hostile environment. This theory was further extended to elliptical shells. The effects of internal ribs located on the inner surface of the facings and the woven facing construction on the response of sandwich structures was studied. In particular, rib-reinforced facings were probably first suggested in the course of the present effort. These new structural concepts are important since woven facings can reduce the tendency to delamination, while rib-reinforced facing results in enhanced local strength and stiffness. Also, the effect of damage in the form of matrix cracks in the facings on the response and performance of sandwich panels was investigated. The similarity conditions for sandwich shells were formulated, jointly with Drs. Simitses, Song and Frostig. The study of a new concept of sandwich structures with truss-reinforced core (Z-fiber reinforced core) was undertaken. The latter design may prove attractive in applications where significant shear and off-axis loads are applied to the structures. Other subjects that were investigated include the evaluation of the shear correction coefficient for sandwich structures analyzed by the first-order theory. The latest effort was a development of an analytical model capable of predicting damping of sandwich structures.

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ADVANCED COMPOSITE MATERIALS FOR THE NEW WORLD VISTAS

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Executive Summary of the Research Pertaining to the Fuselage of the Global Range Transport

During the Mid-1990's the United States Air Force established a clear map for the next fifty years-a study entitled "New World Vistas" The study concluded that the USAF will undergo a major reduction in available overseas base support, and therefore the USAF will be based primarily in the continental United States (CONUS). While at the same time required to provide a global presence. In turn this requires great increases in mobility and faster reaction times. Airlift will, by necessity, deliver the bulk of the fire power in future conflicts. The Air Mobility Command (AMC), which is responsible for global air mobility must be able to provide 49-52 million ton miles per Day, not only for armed conflicts but also for peace keeping and humanitarian missions.

Among the various needs and alternatives, the one key item necessary to fulfill the USAF mission during this next fifty years is the Global Range Transport (GRT). The Global Range transport will become the airlift workhorse for carrying out the task of the AMC, and was scheduled to be available in the year 2020. With its unfueled global reach, and a payload capability from 150,000 to 400,000 lbs. Composite materials are required for the primary construction. Liquid injection molding, reduced parts count, simplified design. increased use of thermoplastics, and increased affordability are all necessary to achieve this goal.

The research conducted, of which this is the Final Report, was tailored specifically to perform the basic research tasks in the important areas of composite materials technology to provide cutting edge knowledge, within the level of support provided, in the following:

1 The behavior of composite shell structures including sandwich configurations, and involving high strain rate effects on material response.

2.Preform design for molding various composites from woven and braided to more usual configurations.

3. Improved manufacturing methods to insure that high quality, low cost composites can be used for the GRT

4. Dynamic and controls research for purposes of vibration suppression and nois reduction.

The interaction of the research efforts are shown clearly in the figure shown on the next page.

The basic research performed during this four year period is included in some detail in the following final reports of the nine investigators, and are presented alphabetically by the researcher's name.

In addition, during the three year period 1998 through 2000, three or more sessions of papers were given each year at the annual ASME-International Mechanical Enginering Conference and Exhibition, which were organized by members of this research team, and in which the majority of the papers presented research which emanated from this research grant.

It is emphasized that one of the verbal challenges presented by the AFOSR personnel at the outset was to see if nine professors at five different universities could conduct a coordinated interactive research program, working together as a team efficient in time and output. This group of researchers have welded together into a cohesive team and have worked very effectively together.

In the original proposal Dr. Robert L. Sierakowski was listed as one of the investigators. Because he became the Chief Scientist of the Munitions Directorate of the USAF, he was not available to work with the research team. The research group was fortunate to have Dr. Ole T. Thomsen, Director of the Institute of mechanical Engineers, Aalborg University, Denmark join the team during the last two years, during which he spent a sabbatical leave at Delaware, and he has made significant contributions to the program.

The research Team wishes to thank the AFOSR for their support during this four year period, and only wishes that the research could continue.

MOLD FILLING SIMULATION OF SANDWICH COMPOSITE STRUCTURES MANUFACTURED BY LIQUID MOLDING: A PARAMETRIC STUDY[1]

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ABSTRACT: The mold filling stage in the manufacturing of sandwich composite structures with fiber reinforced foam core was studied with numerical simulations. Three different geometries of sandwich core reinforcement were considered: in the form of fiber layers forming angle 45^0 or 90^0 with the facings or in the form of equally spaced separate strands (webs). The influence of variable core and face reinforcement permeability and location of the injecting edge on the flow front progression and filling time was explored. The results suggest that permeability of the core has a significant influence on filling pattern and mold filling time. Experimental and predicted flow front developments and flow rates for a radial injection case under constant pressure were compared.

INTRODUCTION

SANDWICH STRUCTURES WITH composite facings are extensively used in the manufacturing of aircraft components because of their lightweight, good mechanical properties and lack of corrosion. Their applications include: control surfaces, vertical and horizontal stabilizers, landing-gear doors, floors, rotor-blades and even all-composite sandwich jet-aircraft[1,2]. Traditionally the materials used in this area are epoxy resins reinforced with carbon or aramid fibers as facings and aluminum or Nomex honeycomb as a core. One promising approach is the use of fiber reinforced polymeric foams as a core material. Most often the sandwich components in aerospace industry are produced in two ways: prepreg lay-up or adhesive bonding[1]. In prepreg lay-up the facings are made of pre-impregnated laminates which are placed directly onto the core and the whole structure is cured under vacuum while in the second case the facings are manufactured separately and then adhesively bonded to the core material. Both methods are suitable for low volume production. The constantly growing consumption of sandwich components along with their increased geometrical complexity requires alternative manufacturing methods. The method with the greatest potential in this respect is Liquid Molding with its variants: RTM, SRIM, and VARTM. These processes allow cost-effective high-volume manufacturing of geometrically complex structures in a single step. In these processes the reinforcement and the core are first placed in the mold cavity and then using pressure or vacuum, liquid resin is introduced to impregnate the reinforcement. After the mold is filled, crosslinking reaction begins, which may be carried out at ambient or higher temperature. The core material usually used in this case is closed cell polymeric foam (polyurethane, polyvinylchloride, polymethacrylimide, etc.). Figure 1 shows three labscale parts made in our composite-manufacturing laboratory. The first two attempts revealed that preform lay-up in addition to impregnation is a crucial issue.

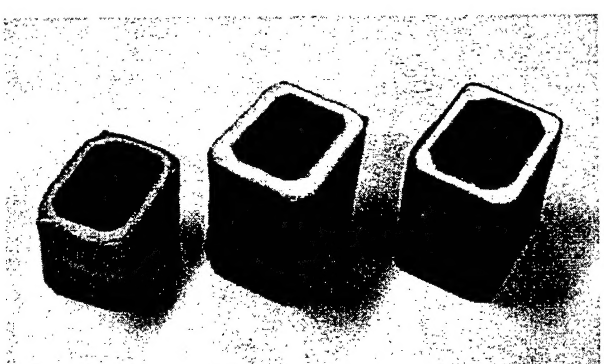

Figure 1 Labscale box-shaped sandwich parts

[1] *Journal of* SANDWICH STRUCTURES AND MATERIALS, Vol.2-April 2000

While the design issues of sandwich structures have been extensively investigated, it appears that there is little detailed information related to the manufacturing of these structures by RTM. Some potential challenges that might arise in this area are described by Al-Hamdan et al.[3] and Wirth et al.[4]. The purpose of this work is to conduct a parametric study using numerical simulation to understand the mold filling stage of sandwich components manufacturing by changing the process variables, reinforcement permeabilities, and core reinforcement geometry. The goal is to find scaling laws that can link the mold filling time with reinforcement properties and processing conditions.

THEORY AND FORMULATION

Modeling of the liquid molding filling stage is based on two equations:
-continuity equation:

$$\nabla \cdot \bar{u} = 0 \tag{1}$$

where $\bar{u}$ is the volume averaged velocity inside the porous media and
-Darcy's law:

$$\bar{u} = -\frac{K}{\eta} \nabla P \tag{2}$$

where η is fluid viscosity, ∇P is the pressure gradient, and K is the permeability tensor of the porous medium[5,7,8]. In sandwich components the thickness of the skins is much smaller than the other dimensions, which allows one to consider the process of liquid molding as two-dimensional. Hence the fluid velocity and pressure gradient are zero in the thickness direction and a two-dimensional form of Darcy's law can be employed as:

$$\begin{pmatrix} \bar{u}_x \\ \bar{u}_y \end{pmatrix} = -\frac{1}{\eta} \begin{pmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{pmatrix} \begin{pmatrix} \partial P/\partial x \\ \partial P/\partial y \end{pmatrix} \tag{3}$$

where $\bar{u}_x$ and $\bar{u}_y$ are Darcy velocities averaged through the face thickness

After applying the continuity equation on equation (3) the following equation for the pressure field is obtained:

$$\frac{\partial}{\partial x}\left(\frac{K_{xx}}{\eta}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{K_{xy}}{\eta}\frac{\partial P}{\partial y}\right) + \frac{\partial}{\partial y}\left(\frac{K_{yx}}{\eta}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{K_{yy}}{\eta}\frac{\partial P}{\partial y}\right) = 0 \tag{4}$$

It is then discretized and solved with the following boundary conditions:

1. At the injection gates – constant pressure or constant flowrate are specified
2. At the flowfront – either atmospheric or vacuum pressure if vacuum assisted injection is used
3. At the mold walls – velocities normal to the mold walls are zero and the pressure gradient is zero.

Once the pressures are determined, control volume approach is used to advance the flow front position at any time during the filling stage[6,7,8].

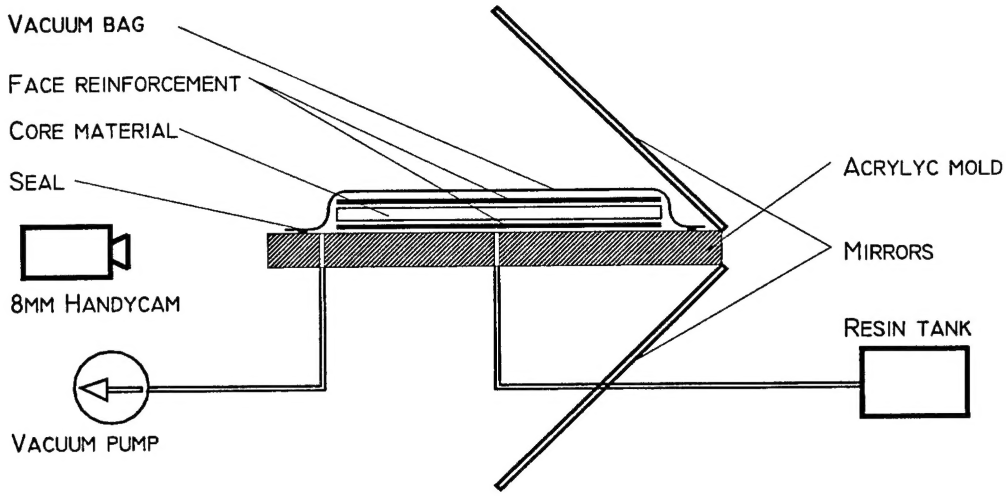

Figure 2 Schematic of experimental setup

A MODEL EXPERIMENT

Schematic representation of experimental setup is shown in fig.2. The dimensions of the sandwich panel were 380 x 304 x 9 mm. The reinforcement of the facings was 2 layers of Knytex E-glass fabric. The core material used in the experiment was WebCore polyocyanurate foam with $\pm45^0$ oriented fiberglass reinforcement placed in layers at a distance 38mm (fig.3). The impregnation was done by subjecting the vent to a vacuum and allowing the fluid to enter under ambient pressure. This created a pressure difference of 1bar. Fluid entered radially from the center of one of the facings. Because of the transparency of mold and vacuum bag the flow front progression along the top and bottom was visible throughout the experiment and was recorded on videotape with the help of 45^0 mirrors. The fluid used to simulate a viscous resin was a mixture of corn syrup, water, and clothing dye with viscosity of 0.17Pa s.

NUMERICAL SIMULATION

All numerical simulations were performed using liquid injection molding simulation (LIMS), a finite element/control volume code developed at the University of Delaware[6]. The LIMS input file contains information about: the mesh (nodes, elements) representing the component; reinforcement material properties such as permeability, volume fraction, thickness; resin properties such as viscosity; position and process conditions at the injection gates and vents. The most important output from simulating the filling process are:

- successive flow front positions, which show how the reinforcement is impregnated
- fill time which is important to know so that one can fill the mold before the resin cross-links
- maximum and inlet values of pressure and flow rate
- pressure distribution along the mold.

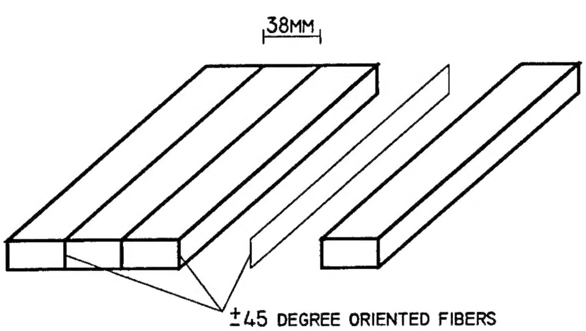

Figure 3 Webcore IVX 150

A comparison of simulated and experimentally obtained filling patterns is shown in fig.4. The simulation of the filling was executed many times with different permeability values for the facings and the core until the experimental flow front progression was closely reproduced. Each black contour in fig.5 represents the position of the flow front at consecutive 10 s. intervals. The permeability values used in the numerical simulation are: $K_x=0.55 \times 10^{-9} m^2$, $K_y=0.7 \times 10^{-9} m^2$ for facing reinforcement and $K=0.1 \times 10^{-9} m^2$ for core reinforcement. The variation in injection flow rate numerically calculated for this experiment is shown in fig.6. The flow rate is initially very high and drops sharply when the fluid comes in contact with the reinforcement.

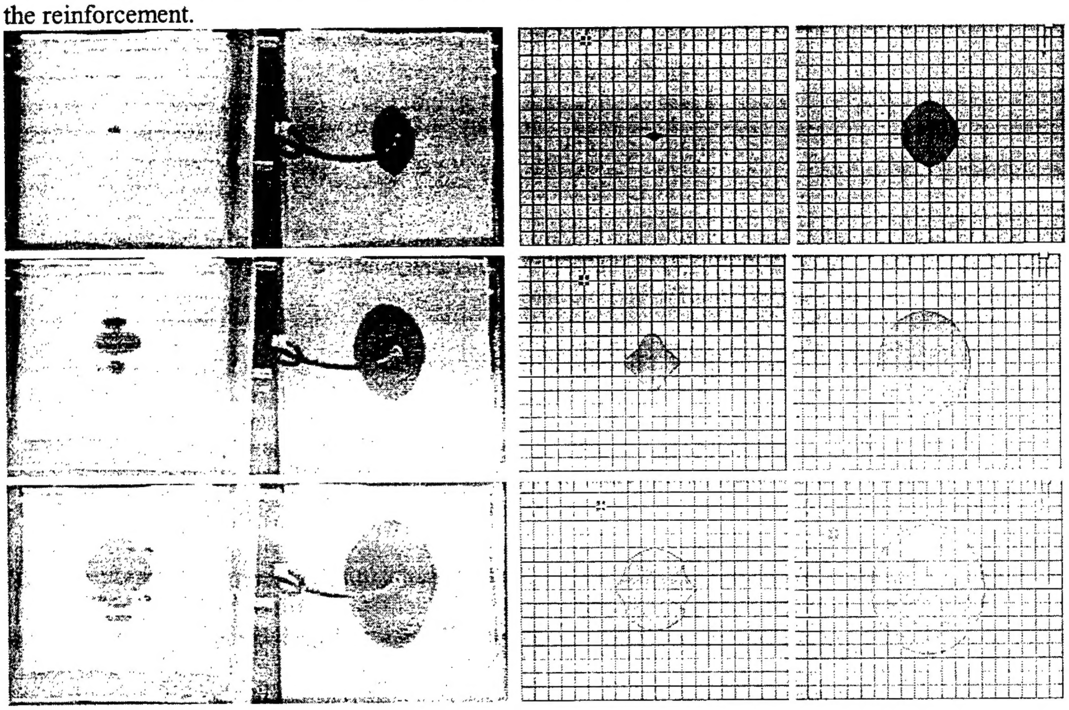

Figure 4 Experimental and simulated filling pattern. From top to bottom: 5,20 and 45s after initial injection

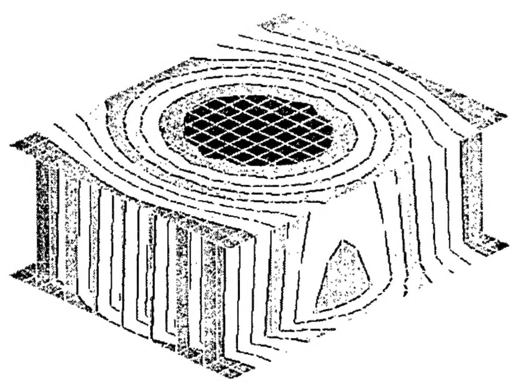

Figure 5 Predicted flowfront development

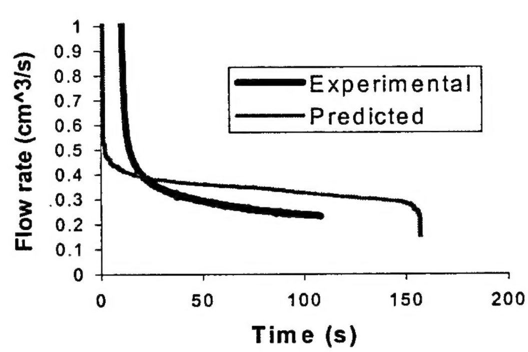

Figure 6 Radial injection flowrate

This validated our approach to study resin impregnation in sandwich structures. Next we conducted parametric case studies to explore flow behavior as a function of permeability ratios of core/facing, types of core material and injection location.

CASE STUDIES

Three basic sandwich geometries were modeled. In all three cases the sandwich structure includes a fiber reinforced foam core, placed between top and bottom layers of fibers, forming the faces of the structure. The type of reinforcement placed in the core makes the distinction between the cases. In case 1 and 2 the fiber mat reinforcement of the core is in the form of a layer forming angles of 90^0 and 45^0 degrees

respectively with the sandwich faces. In case 3 the reinforcement of the core is in the form of separate webs (strands) normal to the facings and placed at a distance of 20mm. The finite element meshes used for the filling simulations are shown in fig.7. The dimensions of each sandwich panel are 100x100x30 mm, while the thickness of the skins was 5mm. The sandwich structure is formed by simultaneously impregnating under vacuum (1bar) the facings and the core reinforcement with liquid resin. In all simulations the volume fraction of the reinforcement was 0.2 and the viscosity of the resin was 0.3 Pas. The injection was done from edge gate denoted by AB in the figures. The goal was to study the influence of gate location, reinforcement type and position in the core, permeability of reinforcement in the face and core on the flow pattern and filling time.

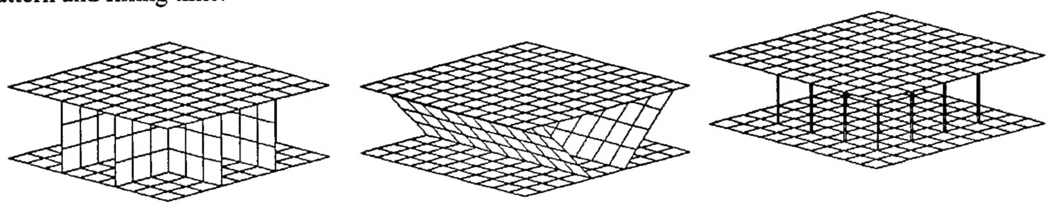

Figure 7 Wire frame model of FE meshes

CASE1. Fig.8 shows the influence of core reinforcement permeability on the filling pattern. From left to right the permeability of the core reinforcement is increased 10 and 100 times. The predicted filling time decreases from 20.96 s to 1.39 s. However, there is high probability of air being trapped inside the right configuration as compared to one on the left. A comparison between simulated and experimentally obtained filling patterns for face/core permeability ratio 0.01 is shown in fig.9. Also in this figure the phenomenon of delayed impregnation can be observed as a lightening of the color of the wetted regions just behind the flow front position.

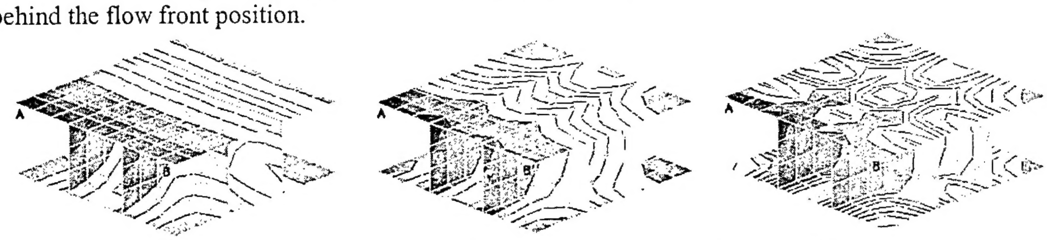

Figure 8 Simulated filling pattern for variable core reinforcement permeability

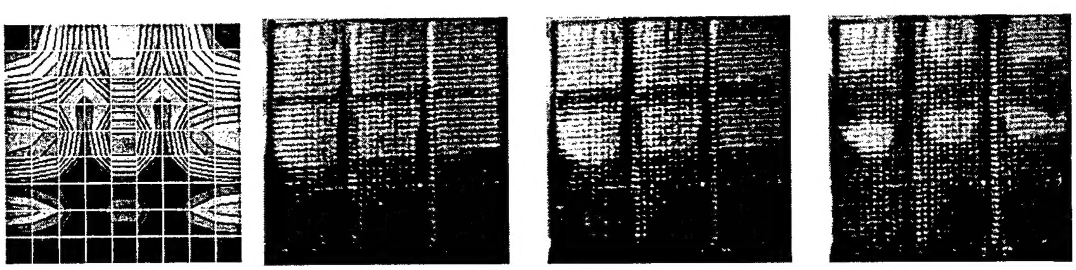

Figure 9 Comparison between simulated and experimentally obtained filling patterns

Fig.10 exhibits the influence of face reinforcement permeability on the filling pattern. From left to right the permeability is increased 10 and 100 times and the filling time drops from 20.96 s to 2.94 s. This result suggests that higher face permeability helps processing in terms of reducing time and also creates flow patterns that do not merge easily, which translates into lower void formation. The relationship between reinforcement permeability ratio and filling time is shown in fig 11(left). After nondimensionalizing the three graphs collapsed into the relation shown in fig. 11(right). This relationship is valid for sandwich panels geometrically similar to the one considered here.

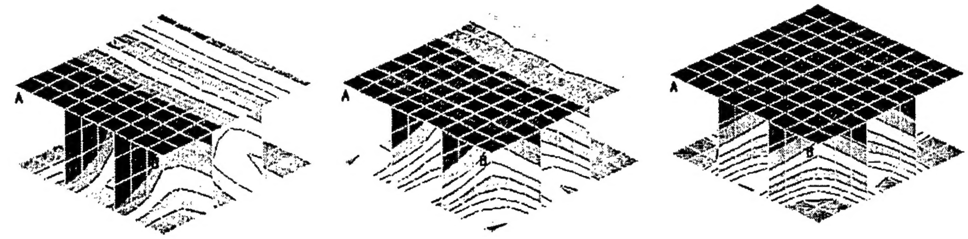

Figure 10 Simulated filling pattern for variable face reinforcement permeability

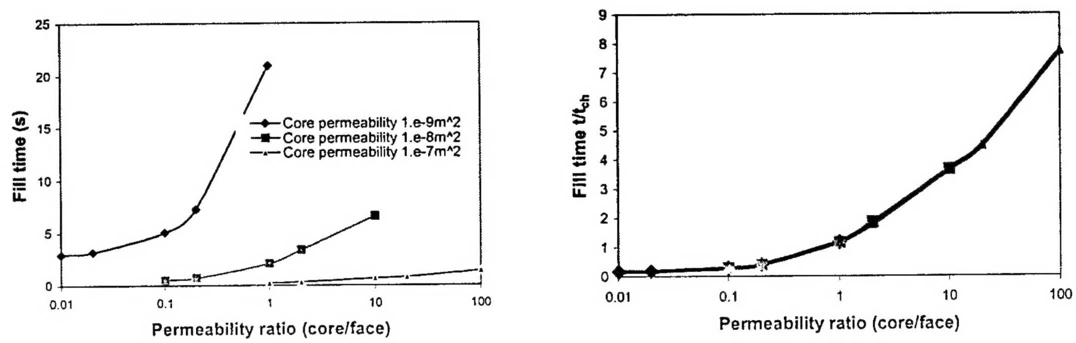

Figure 11 Predicted fill time variation for CASE 1

CASE2. In case 2 the sandwich panel is not symmetric and the influence of the injection edge position was considered. Fig.12 shows flowfront developments and filling times for 4 different positions of the injection edge AB.

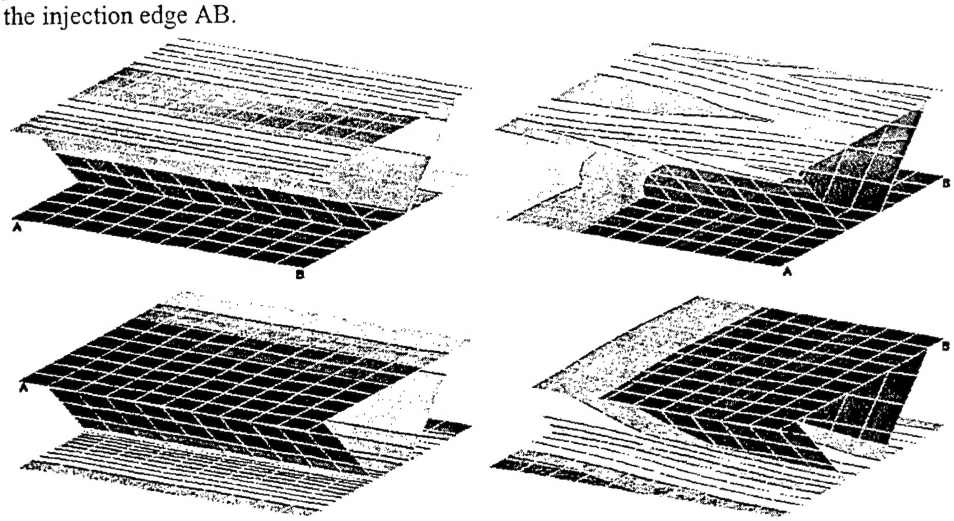

Figure 12 Predicted flowfront patterns for different positions of injecting edge AB

CASE 3. In case 3 the reinforcement of the foam core was in the form of separate webs (strands) normal to the sandwich facings and uniformly spaced at a distance 20 mm. The influence of the reinforcement permeability on the filling pattern and filling time for three different webs cross sections 1x1mm, 3x3mm, 5x5mm, was studied. Fig.13 shows the flow front progression for the case of 3x3mm cross section. The webs permeability increases 10 and 100 times (from $1x10^{-9}m^2$ through $1x10^{-8}m^2$ to $1x10^{-7}m^2$) from left to right in the top row in fig.10. In the bottom row permeability of face reinforcement is increased 10 and 100 times (from $1x10^{-9}$ m^2 through $1x10^{-8}$ $m^2$to $1x10^{-7}m^2$).

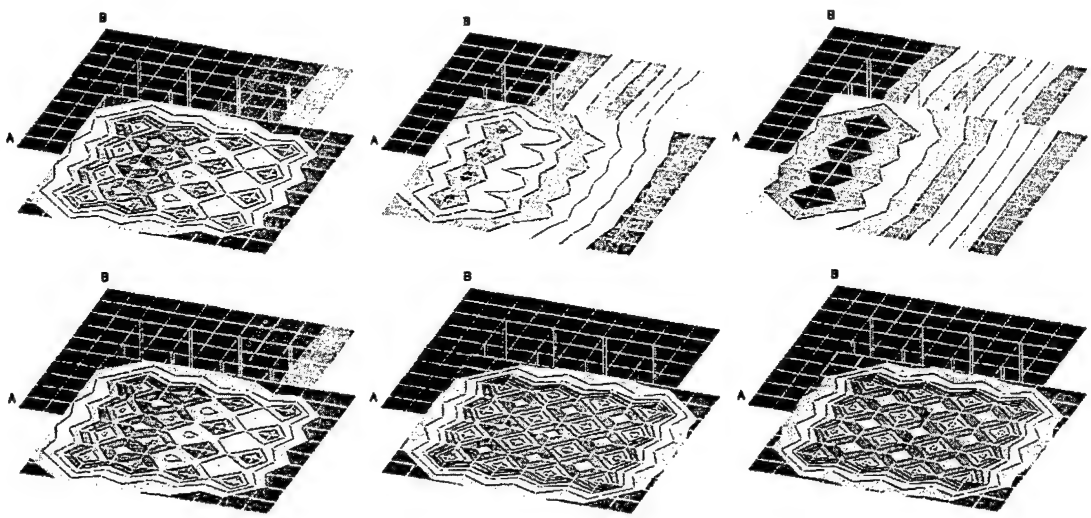

Figure 13 Predicted filling patterns for variable face and core reinforcement permeability in CASE 3

RESULTS AND DISCUSSION

The results of this study show that there are plenty of opportunities to control the filling stage of sandwich components liquid molding. Flow front development and fill time are of major interest and of less interest are pressure distribution and flowrate variation. The opportunities for influence may be grouped into changes in:

- components geometry
- face and core reinforcement permeability
- location and parameters at injection gates and vents.

CASE 1 study demonstrated that by varying only the core and face reinforcement permeability one can achieve full control on the filling time and pattern. For example by increasing the core reinforcement permeability from 1.10^{-9} m^2 to 1.10^{-8} m^2 the fill time is changed from 20.9s to 6.7s. A similar effect might be achieved by changing the facings permeability from 1.10^{-9} m^2 to 5.10^{-9} m^2 - the fill time changes from 20.9s to 7.1s. In general the relationship between fill time and permeability is strongly connected to the volume ratio of core and face reinforcement. So there are a number of ways to achieve certain fill time restrictions imposed by the desire to initiate cure quickly.

Regarding the flow front development the numerical simulations indicated that merging of flowfronts is inevitable in all the cases studied. The only approach to handle this is to evacuate the mold and perform the impregnation under vacuum. In addition by choosing suitable combination of volumes and face and core reinforcement permeability flowfront progression might be directed toward a pattern with less chances for merging or towards the vacuum vent. In fig.13 for example the top right pattern is much more preferred than those on the bottom line. Preliminary scaling law was attempted to describe the role of the core and skin permeability on the fill time. However this law hold only for self-similar geometries with line injection. The goal is to find such a law for all geometries irrespective of changes in location of the inlet gate.

Another important issue to be addressed in future work is related to delayed impregnation (shown in fig.9), which is a consequence of the so called "sink effect"[9-12]. Because of their lower permeability relative to that of inter-tow channels, the fiber tows play the role of sinks absorbing resin even after the flow front has gone by. The extent of this partial saturation and its dependence on mold filling time are directly related to the quality of the sandwich panel.

ACKNOWLEDGEMENTS

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Final and Progress Report - 2001

Victor Birman

2. Objectives

The objectives of the effort of Dr. Birman in the framework of the team effort were to develop a comprehensive theory of aerospace sandwich shells, accounting for thermal effects, and to investigate the effect of various inner reinforcements (ribs on the inner surface of the facings, truss within the core) on global and local response of sandwich structures. In addition, it was necessary to investigate the effect of initial damage, such as matrix cracks in the facings, on the performance. At the final phase of the effort, a methodology for the estimate of damping in sandwich structures was developed (this was beyond the original objectives, but the importance of the accurate prediction of dynamic response and fatigue performance of sandwich panels dictated this additional effort). Some aspects of this work were addressed by Dr. Birman, in collaboration with Dr. G.J. Simitses.

3. Status of Effort

The study of mechanics of sandwich structures and a development of new and innovative structural concepts have been conducted in the course of the effort. In particular, our research was concerned with a development of Sanders'-type theory of cylindrical sandwich shells with different facings operating in hostile environment. This theory was further extended to elliptical shells. The effects of internal ribs located on the inner surface of the facings and the woven facing construction on the response of sandwich structures was studied. In particular, rib-reinforced facings were probably first suggested in the course of the present effort. These new structural concepts are important since woven facings can reduce the tendency to delamination, while rib-reinforced facings result in enhanced local strength and stiffness. Also, the effect of damage in the form of matrix cracks in the facings on the response and performance of sandwich panels was investigated. The similarity conditions for sandwich shells were formulated, jointly with Drs. Simitses, Song and Frostig. The study of a new concept of sandwich structures with truss-reinforced core (Z-fiber reinforced core) was undertaken. The latter design may prove attractive in applications where significant shear and off-axis loads are applied to the structure. Other subjects that were investigated include the evaluation of the shear correction coefficient for sandwich structures analyzed by the first-order theory. The latest effort was a development of an analytical model capable of predicting damping of sandwich structures.

4. Accomplishments and New Findings

The most important findings from the research are:

a. Design of sandwich configurations with different facings may be advantageous. This is because while increasing local strength and stiffness of the facing exposed to external loads, the asymmetry introduced through such design results only in a limited reduction of global strength and stiffness as long as the disparity between the facings is not excessive.

b. Rib-reinforced facings may be an attractive concept since the ribs are beneficial for the strength and stiffness of the corresponding facing. It is preferable to use symmetric designs, even if ribs are not needed on one of the facings. This is because the symmetry of design results in a negligible reduction of global strength and stability that is acceptable in view of the benefits available by using ribs.
c. Matrix cracks limited to transverse layers of the facings result in a small reduction of the natural frequencies, although their effect on the stiffness may be more pronounced. However, as the cracks begin to appear in longitudinal layers, the changes of natural frequencies will be more noticeable.
d. Truss-reinforced cores have to be thoroughly investigated since in spite of their potential advantages, they have a tendency of failing due to the pin pull-through, while pin buckling or delamination are less dangerous in typical configurations.
e. Based on a comparison of six various methods, including three new methods suggested in this research, it is recommended to use a shear correction factor equal to unity for calculations of sandwich structures.
f. A methodology for predicting damping in sandwich structures based on the knowledge of damping of the constituent materials has been developed. The ability to analytically predict damping, dependent on the material and structural parameters of the structure, will be particularly important for designing fatigue-tolerant sandwich structures.

5. Personnel Supported

Research was conducted by Dr. Victor Birman in collaboration with Dr. George Simitses. Graduate student of Dr. Simitses was supported by him (Liang Shen, see details in Dr. Simitses' report).

6. Publications 1998-present

Papers supported by the contract

V. Birman and G.J. Simitses, "Theory of Box-Type Sandwich Shells with Dissimilar Facings Subjected to Thermomechanical Loads", AIAA Journal, Vol. 38, pp. 362-367, 2000.

V. Birman and G.J. Simitses, "Elliptical and Circular Cylindrical Sandwich Shells with Different Facings," Journal of Sandwich Structures and Materials, Vol. 2, pp. 152-175, 2000.

V. Birman, "Transverse Matrix Cracking in a Sandwich Beam with Cross-Ply Facings Subject to a Uniform Pressure," Mechanics Research Communications, Vol. 28, No. 2, 2001.

V. Birman and G.J. Simitses, "Vibration of Sandwich Panels and Beams with Matrix Cracks in the Facings," Composites Science and Technology. In press.

V. Birman, G.J. Simitses and L. Shen, "Stability of Short Sandwich Cylindrical Shells with Rib-Reinforced Facings," Recent Advances in Applied Mechanics, Honorary Volume for Professor A.N. Kounadis, Eds. J.T. Katsikadelis, D.E. Beskos and E.E. Gdoutos, National Technical University of Athens, Athens, Greece, pp. 11-21, 2001.

V. Birman and C.W. Bert, “On the Choice of Shear Correction Factor in Sandwich Structures,” Journal of Sandwich Structures and Materials. In press.

V. Birman and G. J. Simitses, "Theory of Box-Type Sandwich Shells with Dissimilar Facings Subjected to Thermomechanical Loads", Proceedings of the 1998 ASME International Congress, Recent Advances in Mechanics of Aerospace Structures and Materials, Ed. B.V. Sankar, ASME, New York, pp. 151-163, 1998.

G.J. Simitses, G. Song and V. Birman, “Similarity Conditions for Cylindrical and Flat Sandwich Panels”, Proceedings of the 1999 ASME Summer Applied Mechanics and Materials Conference, Eds. R.C. Batra and E.G. Henneke, ASME Press, New York, p. 324.

G.J. Simitses, G. Song, V. Birman and Y. Frostig, “Similarity Conditions for Sandwich Shell-Like Configurations”, Proceedings of the 1999 ASME International Congress. Advances in Aerospace Materials and Structures, Ed. G. Newaz, ASME (AD-Vol. 58), New York, pp. 65-78, 1999.

V. Birman and G.J. Simitses, “Stability of Cylindrical Sandwich Shells with Dissimilar Facings”, Proceedings of the 1999 ASME International Congress. Advances in Aerospace Materials and Structures, Ed. G. Newaz, ASME (AD-Vol. 58), New York, pp. 41-51, 1999.

V. Birman and G.J. Simitses, “Theory of Elliptical Sandwich Cylindrical Shells with Dissimilar Facings”, Proceedings of the 12th International Conference on Composite Materials, Paris, July 1999. Available on a CD disc.

V. Birman and G.J. Simitses, “Theory of Cylindrical Sandwich Shells with Dissimilar Woven Facings”, Proceedings of the 1999 American Society for Composites Conference (Fourteenth Technical Conference), Ed. J.W. Whitney, Technomic, Lancaster, pp.395-402, 1999.
“Sandwich”

V. Birman and G.J. Simitses, “Vibrations of Sandwich Panels with Matrix Cracks in the Facings,” Sandwich Construction 5, Vol. II, Eds. H.-R. Meyer-Piening and D. Zenkert, EMAS Publishers, Zurich, pp. 753-764, 2000.

V. Birman, G.J. Simitses and L. Shen, “Stability of Sandwich Cylindrical Shells with Stiffened Facings,” Mechanics of Sandwich Structures (AD-Vol. 62 and AMD-Vol. 245), Eds. Y.D.S. Rajapakse, G.A. Kardomateas and V. Birman, ASME Press, New York, pp. 101-115, 2000.

V. Birman and C.W. Bert, “On the Choice of Shear Correction Factor in Sandwich Structures,” Mechanics of Sandwich Structures (AD-Vol. 62 and AMD-Vol. 245), Eds. Y.D.S. Rajapakse, G.A. Kardomateas and V. Birman, ASME Press, New York, pp. 277-285, 2000.

A. Tabiei, R. Tanov and V. Birman, “Sandwich Shell Finite Element for Dynamic Explicit Analysis,” Mechanics of Sandwich Structures (AD-Vol. 62 and AMD-Vol. 245), Eds. Y.D.S. Rajapakse, G.A. Kardomateas and V. Birman, ASME Press, New York, pp. 245-227, 2000.

C. Kocher, W. Watson, M. Gomez, I. Gonzalez and V. Birman, “Integrity of Multi-Skin Sandwich Panels and Beams with Truss-Reinforced Cores,” The 2001 AIAA Structures, Structural Dynamics and Materials Conference. Also, AIAA Paper 00-1637.

V. Birman and L.W. Byrd, "On the Prediction of Damping in Composite and Sandwich Structures," The Proceedings of the 2001 International Mechanical Engineering Congress, November 2001, ASME Press, New York. In press.

<u>Other publications during the contract period (1998-present)</u>

V. Birman, "On Mode I Fracture of Shape Memory Alloys", Smart Materials and Structures, Vol. 7, pp. 433-437, 1998.

C.W. Bert and V. Birman, "Effects of Stress and Electric Field on the Coefficients of Piezoelectric Materials: One-Dimensional Formulation", Mechanics Research Communications, Vol. 25, pp. 165-169, 1998.

V. Birman, "On the Effect of Cyclic Loading on Material Temperature", Mechanics Research Communications, Vol. 25, pp. 653-660, 1998.

V. Birman, "Analysis of Shape Memory Alloy Plate with a Circular Hole Subjected to Biaxial Tension", International Journal of Solids and Structures, Vol. 36, pp. 167-178, 1999.

L.W. Byrd and V. Birman, "Theoretical Foundations for Nondestructive Detection of Cracks in Ceramic Matrix Composites Based on Surface Temperature", Composite Structures, Vol. 48, pp. 71-77, 1999.

C.W. Bert and V. Birman, “Stress Dependency of the Thermoelastic and Piezoelectric Coefficients,” AIAA Journal, Vol. 37, pp. 135-137, 1999.

V. Birman and L.W. Byrd, “Analysis of Ceramic Matrix Composites with Bridging Cracks in the Presence of Creep,” Transaction of the Canadian Society of Mechanical Engineers, Vol. 22, pp. 447-456, 1998.

V. Birman, G.J. Knowles and J.J. Murray, “Application of Piezoelectric Actuators to Active Control of Composite Spherical Caps”, Smart Materials and Structures, Vol. 8, No. 2, pp. 218-222, 1999.

V. Birman, S. Griffin and G.J. Knowles, “Axisymmetric Dynamics of Composite Spherical Shells with Active Piezoelectric/Composite Stiffeners”, Acta Mechanica, Vol. 141, No. 1/2, 2000.

V. Birman and L.W. Byrd, “Applications of Thermography to Detection of Matrix Cracks in Transverse Layers and Yarns of Ceramic Matrix Composites,” International Journal of Fracture, Vol. 102, pp. L21-L-26, 2000.

V. Birman, "Stiffness of Smart Composites with Shape Memory Alloy Fibers in the Presence of Matrix Cracks," Journal of Intelligent Material Systems and Structures, Vol. 10, pp. 135-140, 2000.

V. Birman and L.W. Byrd, "Fracture and Fatigue in Ceramic Matrix Composites," Applied Mechanics Reviews, Vol. 53, pp. 147-174, 2000.

V. Birman and L.W. Byrd, "Selected Issues of Mechanics of Ceramic Matrix Composites," Composite Structures, Vol. 51, pp. 181-190, 2001.

V. Birman and L.W. Byrd, "Matrix Cracking in Transverse Layers of a Cross-Ply Beam Subjected to Bending and Its Effect on Vibration Frequencies," Composites Part B: Engineering, Vol. 32B, pp. 47-55, 2001.

L.W. Byrd and V. Birman, "Nondestructive Testing of Thin-Walled Ceramic Matrix Composites Using Thermography," Advances in Mechanics of Plates and Shells," Eds. D. Durban, J.G. Simmonds and D. Givoli, Kluwer Academic Publishers, Dordrecht, pp. 103-118, 2001

V. Birman and L.W. Byrd, "Natural Frequencies of Cross-Ply Laminated Panels with Matrix Cracks," AIAA Journal, Vol. 39, No. 1, pp. 190-193, 2001.

V. Birman and L.W. Byrd, "Effect of Matrix Cracking in Cross-Ply Ceramic Matrix Composite Beams on Their Mechanical Properties and Natural Frequencies," International Journal of Non-Linear Mechanics. In press.

L. Byrd and V. Birman, "Review of Fracture and Fatigue in Ceramic Matrix Composites", Report AFRL-VA-WP-TR-1999-3023, Wright-Patterson AFB, 1999.

C.W. Bert and V. Birman, "Modeling of a Shape-Memory Alloy Sheet with a Circular Hole and Subjected to Arbitrary In-plane Loading", Proceedings of the 5th Annual International Symposium on Smart Materials and Structures, Mathematics and Control in Smart Structures, Ed. V.V. Varadan, SPIE, Vol. 3323, pp. 503-511, 1998.

V. Birman and L. Byrd, "Creep of Unidirectional Ceramic Matrix Composites with Matrix Cracks", Proceedings of the Canadian Society for Mechanical Engineering (CSME) Forum, Ryerson Polytechnic University, Toronto, Canada, Vol. 2, pp. 65-70, 1998.

L.W. Byrd and V. Birman, "Theoretical Foundations for Nondestructive Detection of Cracks in Ceramic Matrix Composites Based on Surface Temperature", Proceedings of the Second International Conference on Composite Science and Technology, Eds. S. Adali, E.V. Morozov and V.E. Verijenko, University of Natal, Durban, South Africa, pp. 495-500, 1998.

J. Murray, G.J. Knowles, and V. Birman, "Piezoelectronics Theory of Composite Spherical Shells", Proceedings of the 4th European Conference on Smart Structures and Materials, Eds. G.R. Tomlinson and W.A. Bullough, Institute of Physics Publishing, Bristol, England, pp. 635-642, 1998.

V. Birman, "Temperature Rise in Materials Subjected to Rapid Cyclic Loading", Proceedings of the 2nd International Conference on Non-Linear problems in Aviation and Aerospace, Daytona Beach, Florida, Ed. S. Sivasundaram, European Conference Publications, Cambridge, UK, Vol. 1, pp. 119-126, 1999.

V. Birman and L.W. Byrd, "Stiffness of Woven Ceramic Matrix Composites with Matrix Cracks", Proceedings of the 40th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Vol. 2, AIAA, Washington, DC, pp. 1135-1143, 1999 (AIAA Paper AIAA-99-1331).

V. Birman, "Stiffness of Smart Composites with Shape Memory Alloy Fibers in the Presence of Matrix Cracks," Proceedings of the 1999 SPIE Symposium on Smart Structures and Materials, Mathematics and Control in Smart Structures, Ed. V.V. Varadan, SPIE, Vol. 3667, Bellingham, Washington, pp. 578-585, 1999.

V. Birman and L.W. Byrd, "Theoretical Foundations of Using Thermography for Nondestructive Detection of Matrix Cracks in Woven Ceramic Matrix Composites", Proceedings of the Second International Workshop for Health Monitoring, Stanford University, Stanford, California, Structural Health Monitoring, Ed. F.-K. Chang, Technomic, Basel, pp. 821-829, 1999.

C.W. Bert and V. Birman, "Bending and Stretching of a Rotating Circular Plate with Moderate Tilt", AIAA paper AIAA 99-1304, 1999.

V. Birman, "Research Issues Related to Industrial Applications of Ceramic Matrix Composites," Proceedings of the 3rd International Conference on Composite Science and Technology (ICCST/3), Eds. S.Adali, E.V. Morozov and V.E. Verijenko, University of Natal, Durban, South Africa, pp. 1-20, 2000.

V. Birman and L.W. Byrd, "Vibrations of a Cross-Ply Ceramic Matrix Composite Beam with Matrix Cracks in Longitudinal and Transverse Layers," The 10th International Congress on Fracture. In press.

V. Birman and L.W. Byrd, " Damping in Unidirectional and Cross-Ply Ceramic Matrix Composites with Matrix Cracks," The Proceedings of the 2001 International Mechanical Engineering Congress, November 2001, ASME Press, New York. In press.

7. Interactions/Transitions

a. Participation in Conferences (only the papers supported by the contract are listed):

V. Birman and G.J. Simitses, "Theory of Box-Type Sandwich Shells with Dissimilar Facings Subjected to Thermomechanical Loads", The 1998 ASME Mechanical

Engineering Congress and Exposition, Anaheim, California, November 1998.

G.J. Simitses, G. Song and V. Birman, "Similarity Conditions for Cylindrical and Flat Sandwich Plates", The 1999 ASME Summer Applied Mechanics Meeting, Blacksburg, Virginia, June 1999.

V. Birman and G.J. Simitses, "Theory of Elliptical Sandwich Cylindrical Shells with Dissimilar Facings", The 12th International Conference on Composite Materials, Paris, July 1999.

V. Birman and G.J. Simitses, "Theory of Cylindrical Sandwich Shells with Woven Dissimilar Facings," The 14th Annual Technical Conference of the American Society for Composites, Dayton, Ohio, September 1999.

V. Birman and G.J. Simitses, "Stability of Cylindrical Sandwich Shells with Rib-Reinforced Facings," The 1999 ASME International Mechanical Engineering Congress, Nashville, Tennessee, November 1999.

V. Birman and G.J. Simitses, "Stability of Cylindrical Sandwich Shells with Dissimilar Facings," The 1999 ASME International Mechanical Engineering Congress and Exposition, Nashville, Tennessee, November 1999.

G.J. Simitses, G. Song, V. Birman and Y. Frostig, "Similarity Conditions for Sandwich Shell-Like Configurations," The 1999 ASME International Mechanical Engineering Congress and Exposition, Nashville, Tennessee, November 1999.

V. Birman and G,J, Simitses, "Vibration of Sandwich Panels with Matrix Cracks in the Facings," The Fifth International Conference on Sandwich Construction, Zurich Switzerland, September 2000.

V. Birman, G.J. Simitses and L. Shen, "Stability of Sandwich Cylindrical Shells with Stiffened Facings," The 2000 International Mechanical Engineering Congress and Exposition, Orlando, Florida, November 2000.

V. Birman and C.W. Bert, "On the Choice of Shear Correction Factor in Sandwich Structures," The 2000 International Mechanical Engineering Congress and Exposition, Orlando, Florida, November 2000.

A. Tabiei, R. Tanov and V. Birman, "Sandwich Shell Finite Element for Dynamic Explicit Analysis," The 2000 International Mechanical Engineering Congress and Exposition, Orlando, Florida, November 2000.

C. Kocher, W. Watson, M. Gomez, I. Gonzalez and V. Birman, "Integrity of Multi-Skin Sandwich Panels and Beams with Truss-Reinforced Cores," The 2001 AIAA Structures, Structural Dynamics and Materials Conference. Seattle, April 2001.

V. Birman, "Selected Issues of Theory and Design of Sandwich Panels," Composites for Marine Structures, Office of Naval Research Review, University of Maryland, May 2001.

V. Birman and L.W. Byrd, "On the Prediction of Damping in Composite and Sandwich Structures," The 2001 International Mechanical Engineering Congress and Exposition (IMECE 2001), Symposium Dynamic Failure in Composite Materials. New York, November 2001.

b. Consulting:

Consulting Air Force Research Laboratory (WPAFB, Dayton, Ohio) on mechanics and nondestructive damage detection in ceramic matrix composites. Contact: Dr. Larry W. Byrd. This work has been conducted during the reported period.

Consulting Qortek, Inc. (Williamsport, Pennsylvania) on the innovative structural design of piezoelectric actuators. Contact: Dr. Gareth Knowles. Spring 2000. Development of the Thunder concept for miniature munitions. Summer 2001-present.

Consulting Design Optimization Technologies (St. Louis, Missouri) on a multitude of technical problems, including civil engineering structures certifications, thermal analysis of an airborne camera pad for reconnaissance planes, choice of transparent elements for aerospace equipment, etc. 2000. Contact: Mr. Ildelfonso Gonzalez.

c. Transitions: See the previous paragraph (consulting). Industrial problems considered for Qortek and Design Optimization Technologies.

8. New discoveries: none.

9. Honors and awards (including appropriate professional activities)

Victor Birman:

- ♦ Included into Who's Who in America (55th Edition, 2001, 56th Edition, 2002)
- ♦ Included into Who's Who in the World (2000)
- ♦ Included into Who's Who in America (Science and Engineering, 5th Edition, 2000, 6th Edition, 2001)
- ♦ Co-Editor of the book "Mechanics of Sandwich Structures," ASME, New York, 2000.
- ♦ Co-organizer of the Symposium Honoring Professors Charles W. Bert and Jack Vinson at the 1999 ASME International Mechanical Engineering Congress and Exposition, Nashville, Tennessee, November 1999.
- ♦ Co-organizer of the Symposium "Mechanics of Sandwich Structures" at the 2000 ASME International Mechanical Engineering Congress and Exposition, Orlando, Florida November 2000.
- ♦ Co-organizer of the Symposium Honoring Professor George J. Simitses at the 2001 ASME International Mechanical Engineering Congress and Exposition, New York, New York, November 2001.
- ♦ University of Missouri-Rolla Faculty Excellence Award (1999-2000).
- ♦ Member of the International Advisory Board of the Third International Conference on Composite Science and Technology (January 11-13, 2000, Durban, South Africa)

♦ Member of the International Advisory Board of the Seventh International Conference on Composites Engineering (July 2001, Denver, Colorado).

♦ Chairman of the sessions "Fracture, and Composites I", at the Canadian Society for Mechanical Engineering Forum 98, Ryerson Polytechnic University, Toronto, Canada, May 19-22, 1998.

♦ Chairman of the session "Shape Memory Alloys II" at the SPIE's 6th Annual International Symposium on Smart Structures and Materials, Newport Beach, California,March 4, 1999.

♦ Chair of two sessions at the 1999 ASME International Mechanical Engineering Congress and Exposition (these sessions were a part of the symposium honoring Professors C.W. Bert and J.R. Vinson), Nashville, Tennessee, November 1999.

♦ Co-chair of the session "Experimental Mechanics II" at the Seventh International Conference on Composites Engineering, Denver, Colorado, July 4, 2000.

♦ Chair of the session "Mechanics of Sandwich Structures VI" at the 2000 ASME International Mechanical Engineering Congress and Exposition, Orlando, Florida, November 2000.

Final Report to AFOSR
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ADVANCED COMPOSITE MATERIAL RESEARCH FOR THE NEW WORLD VISTAS:

TEXTILE PREFORM DESIGN, ANALYSIS AND FABRICATION FOR LIGHT-WEIGHT DAMAGE TOLERANT COMPOSITES

Prepared by

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J. L. Nowinski Professor of Mechanical Engineering

Bryan A. Cheeseman
Post-Doctoral Fellow

I. Introduction

As part of the AFOSR Advanced Composite Materials for the New World Vistas program, the development of what may become the world's largest aircraft, the Global Range Transport (GRT), demands the latest in aircraft design and construction. Towards these ends, Vinson and co-workers are studying all of the basic structural, material and manufacturing aspects of the fuselage structure. Innovative fuselage designs consisting of sandwich structures that are subjected to biaxial, torsional, bending and transverse shear loadings have been investigated and it has been shown that with a insightful choice of unsymmetric face sheets, deleterious stresses can be reduced. Although laminated composites are being studied, the application of textile composite sandwich structures is also being considered. The scope of the effort to apply textile structural composites is depicted in Figure 1 and summarized as follows.

II. Textile Preforming Technology

When designing with textile composites, the geometry and loading configuration of the structure being considered determines the fiber architectures and textile preforming techniques that can be utilized. A number of recent advances in textile preforming technology has led to the increased mechanical performance of textile composites. Some of these preforming technologies are now commercially available and could influence the choice of textile structural composite being considered in the current project. Notable among these are weaving looms having the ability to introduce off-axis (bias) fibers for improved in-plane shear properties and several different technologies that improve out-of-plane properties and damage tolerance of the textile composites by the introduction of fibers in the third direction. A summary of an assessment of the state-of-the-art in textile preforming and their relationship to basic structural elements under a variety of loading configurations was presented at the Symposium on Sandwich Construction for Large Transport Aircraft of the ASME Winter Annual Meeting in November 1998 [1] and a comprehensive examination of this has been performed and was published in *Composites Science and Technology* [2].

III. Integral Structures

Textile structural composites also offer the capability of near-net-shape manufacturing. These integral structures make possible the saving of manufacturing time by allowing the integration of several parts into one fiber preform and may also improve the structural performance of the part by providing additional fiber reinforcement that could prevent delamination of traditional designs. An integral structure that is relevant to this particular project is a sandwich structure having a core, face sheets and a connection between the face sheets. By connecting the face sheets, the integral sandwich structure provides reinforcement against the delamination of the face sheets, one of the most common failure modes of sandwich structures. Such integral sandwich structures have been produced by weaving, knitting and a novel fiber insertion process developed by Toyoda Automatic Loom Works, Ltd. This technique employs a base frame system, shown in Figure 2(a) on which are arranged a system of guide pins that can be configured to form a variety of complex three-dimensional shapes. As shown in Figure 2(b)-(e), dry

yarns are looped around the guide pins in a variety of orientations. In order to minimize fiber damage when the through-the-thickness fibers are introduced, the guide pins are configured so the inter-yarn spacings allow for the easy insertion of these fibers. The through-the-thickness yarns are inserted with a fiber thrusting apparatus shown in Figure 2(f). This device consists of multiple needles which enables high productivity. After the yarns are looped around the guide pins, the through-the-thickness yarns are then inserted through this arrangement and looped over a selvage yarn which binds the preform together.

With its inherent flexibility to produce complex three-dimensional shapes, the fiber insertion process was identified as particularly promising to the current investigation. Toyoda Automatic Loom Works, Ltd., agreed with us at the University of Delaware to test the feasibility of producing integral sandwich structures with this method. A protoype sandwich structure, consisting of carbon fiber face sheets and a foam core was readily produced and it was seen that the process is easily scalable.

IV. Textile Composite Stiffness Model (TCSM)

The Textile Composite Stiffness Model (TCSM) software is being developed to aid in the design of textile composite sandwich structures. The TCSM is user-friendly, graphically oriented computer program that an engineer with little prior knowledge of the intricacies of thermo-elastic modeling of textile structural composites can use to calculate their thermo-elastic properties. By using the Visual Basic programming language within Microsoft Excel, the program is capable of running on either a Windows or Macintosh platform. A portion of this program was presented at the Symposium in Honor of Stephen Tsai on July 2-4, 1999 [3], and an example of the graphical nature of the program can be seen in the input window shown in Figure 3 for a layer-to-layer weave. For two-dimensional woven composites, the program uses the classic mosaic, crimp and bridging models and for three-dimensional textile composites, the TCSM utilizes the Effective Response Comparison (ERC) model developed by Pochiraju and Chou [4,5]. Since the ERC model is based upon the representative volume element representation of a three-dimensional textile composite, many different fiber architectures can be modeled [6].

V. Damage Considerations

Damage tolerance is an important consideration in the application of composites to structural aircraft components. Laminated composites typically exhibit poor damage tolerance due to their low resistance to delamination. Textile composites having reinforcement in three directions offer superior delamination strength due to the presence of reinforcing fibers in the thickness direction. Commercially available textile preforming techniques such as weaving, braiding, knitting and stitching offer a cost-effective way of introducing through-the-thickness fibers. As part of the current investigation, the effect of stitching on the Mode I fracture toughness and in-plane properties for a quasi-isotropic carbon/epoxy laminate has been studied. Stitch size and density were also examined and as shown in Figure 4, stitching has a pronounced effect on the Mode I fracture toughness. Although it has been previously reported that stitching

degrades in-plane properties, it has been shown that for small stitch sizes, in-plane properties are not adversely affected [7].

Since damage tolerance is an important consideration in aircraft structures, the ability to predict the effect of damage on the structural performance of an aircraft component would be useful when designing the novel fuselage structure. The current investigation is considering two different approaches to the modeling of damage in composite materials. One approach accounts for the different failure modes of the constituents on a micromechanical scale. The micromechanical failures result in a corresponding decrease in the overall mechanical properties of the composite. One such damage model has been recently developed by Pochiraju and Chou [8]. Known as the Multi-Scale Multi-Grid (MSMG) model, it is incorporated into the finite element code ABAQUS as a user-defined material and accounts for a change in elemental stiffness due to microstructural damage/failure. By coupling the damage model with FEA, the effect of microstructural damage on the structural performance of a composite component can be calculated. Since the Multi-Scale Multi-Grid (MSMG) model employs the ERC model for the calculation of the stiffness, the MSMG model can have the capabilities of modeling many different textile composites [9]. Also, by integrating the MSMG model into a commercial finite element package, many complex structural components can also be analyzed.

Another modeling approach to damage in composites is made on a continuum or macroscale. In this approach, damage is considered to be the development of microdefects that ultimately leads to the failure of the material. This gradual growth of microdefects can be described by the degradation of the elastic properties of the material. This type of damage modeling does not account for the failures of the composite constituents on the micromechanical scale, rather it describes damage through the introduction of a damage state variable. Recently, an anisotropic continuum damage model for textile composites has been developed where the damage kinematics are determined with only one second-order tensor variable [10]. Recent work in applying this damage model to woven orthogonal interlock carbon fiber-epoxy composites was presented at the ICCE-12 [11].

VI. Publications

1. Chou, T. W., Kamiya, R. and Cheeseman, B. A. "An Assessment of the Textile Preform Technology for Structural Composites." *Symposium on Sandwich Construction for Large Transport Aircraft, The International Mechanical Engineering Congress & Exposition*, November 15-20, 1998, Anaheim CA

2. Kamiya, R., Cheeseman, B. A., Popper, P. and Chou, T. W. "Some Recent Advances in the Fabrication and Design of Three-dimensional Textile Preforms: A Review." *Composites Science and Technology*, **60**, 33, 2000.

3. Cheeseman, B. A., Pochiraju, K. and Chou, T. W. "A Computer Software Package for Thermo-elastic Property Prediction of 3-D Textile Structural Composites."

Composites for the Next Millenium: A Symposium in Honor of Stephen W. Tsai on His 70th Birthday July 2-3, 1999, Tours, France.

4. Pochiraju, K. and Chou, T. W. "Three-dimensionally Woven and Braided Composites I: A Model for Anisotropic Stiffness Prediction." *Polymer Composites*, **20**, 565, 1999.

5. Pochiraju, K. and Chou, T. W. "Three-dimensionally Woven and Braided Composites II: An Experimental Characterization," *Polymer Composites*, **20**, 733, 2000.

6. Cheeseman, B. A. and T. W. Chou. *Textile Composite Stiffness Model (TCSM) Software*. 2000.

7. Kamiya, R. and Chou, T. W. "Strength and Failure Behavior of Stitched Carbon/Epoxy Composites," *Metallurgical and Materials Transactions A*, **31A**, 899, 2000.

8. Pochiraju, K., Parvizi-Majidi, A. and Chou, T. W. "Modeling Damage in Rigid Textile Composite Structures" *ASME International Mechanical Engineering Congress and Exposition*, Nov. 6-11, Chicago. 1994.

9. Pochiraju, K., Cheeseman, B. A. and Chou. T. W. "Damage Modeling of Sandwich Structures with a Multi-Scale Multi-Grid Model." in preparation

10. Gasser, A., Ladeveze, P, and Peres, P. "Damage Modelling for a Laminated Ceramic Composite." *Materials Science and Engineering A*, 250, 249-255. 1998.

11. "Damage Behavior of a Three-Dimensional Woven Composite" *Proceedings of the ICCM-12*, July 5-9, Paris, 1999.

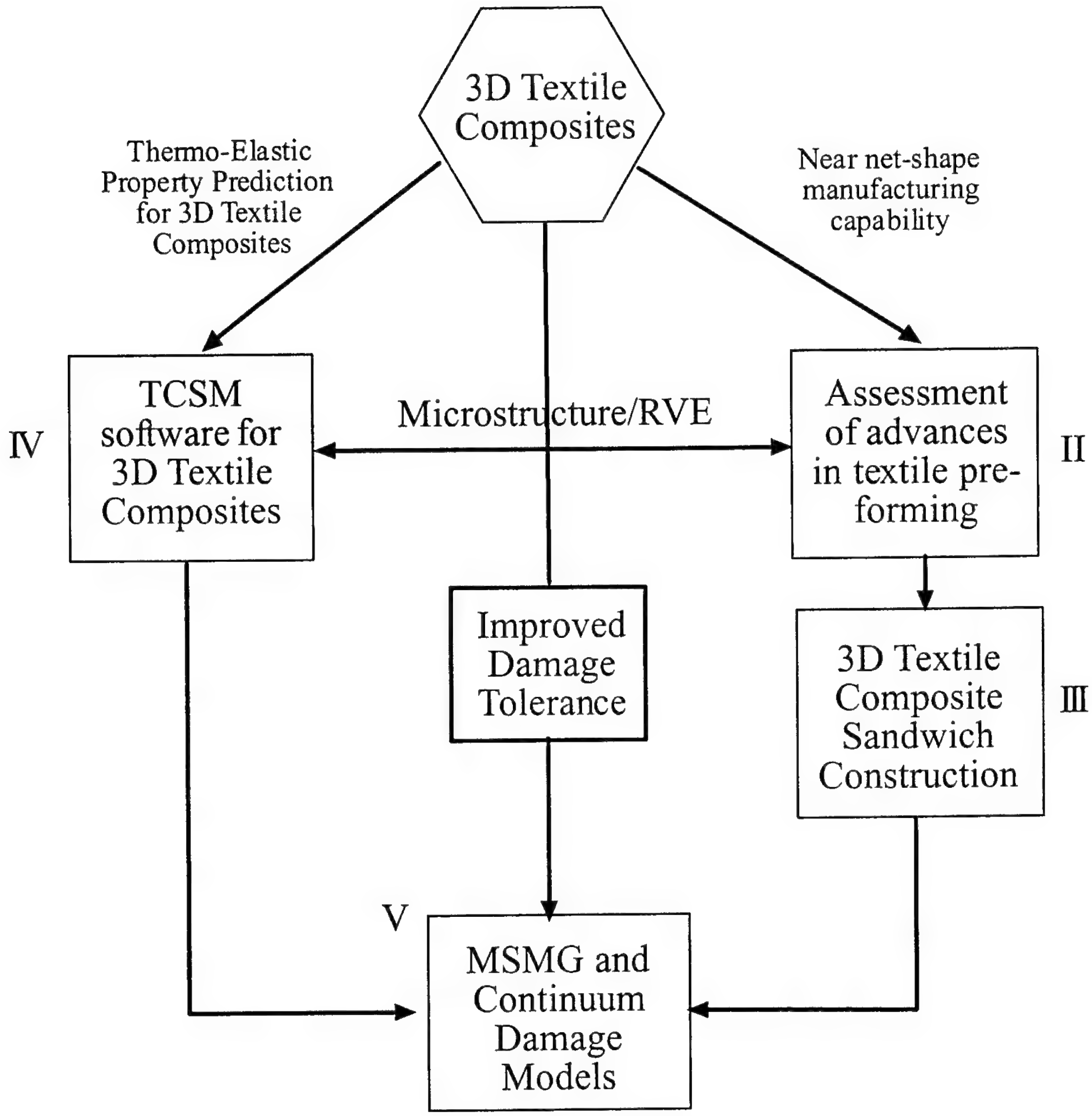

Figure 1: Flowchart of current effort to apply textile composites to the fuselage structures of the Global Range Transport (II, III, IV and V correspond to the section numbers of this report).

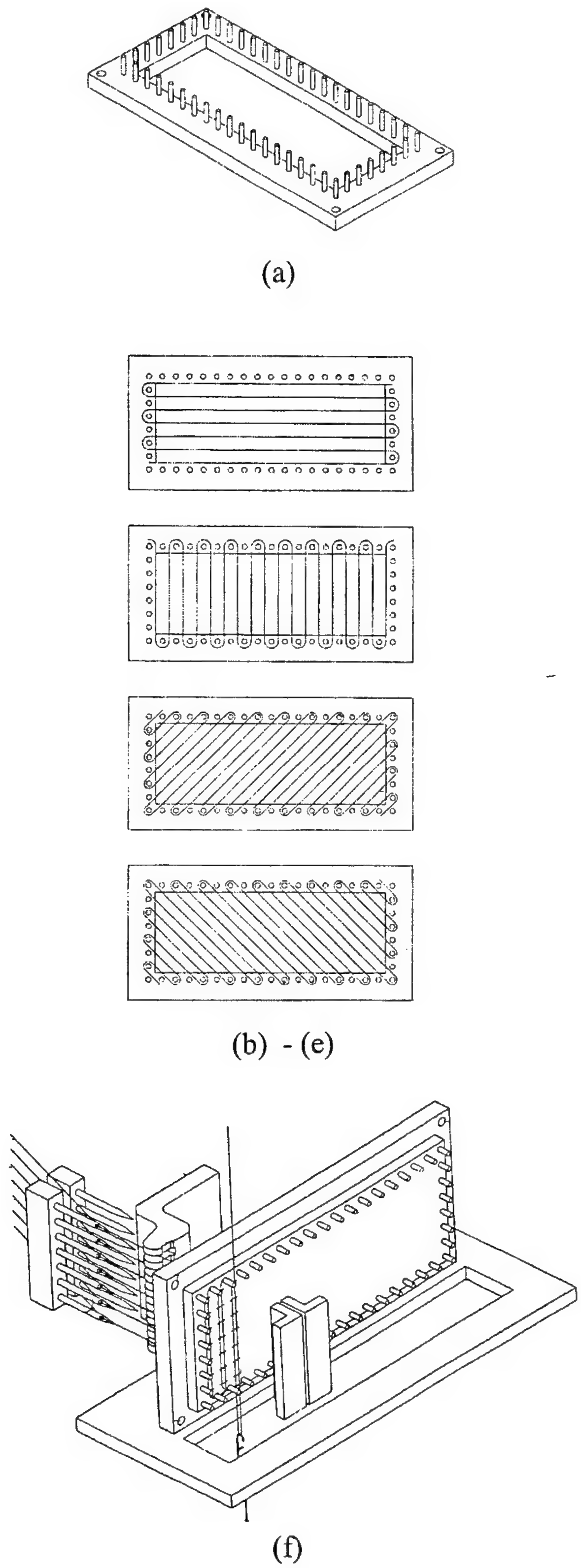

Figure 2: (a) Base pin and guide pins for the fiber insertion technique, (b) – (e) dry yarns oriented around guide pins along various orientations, (f) fiber thrusting apparatus.

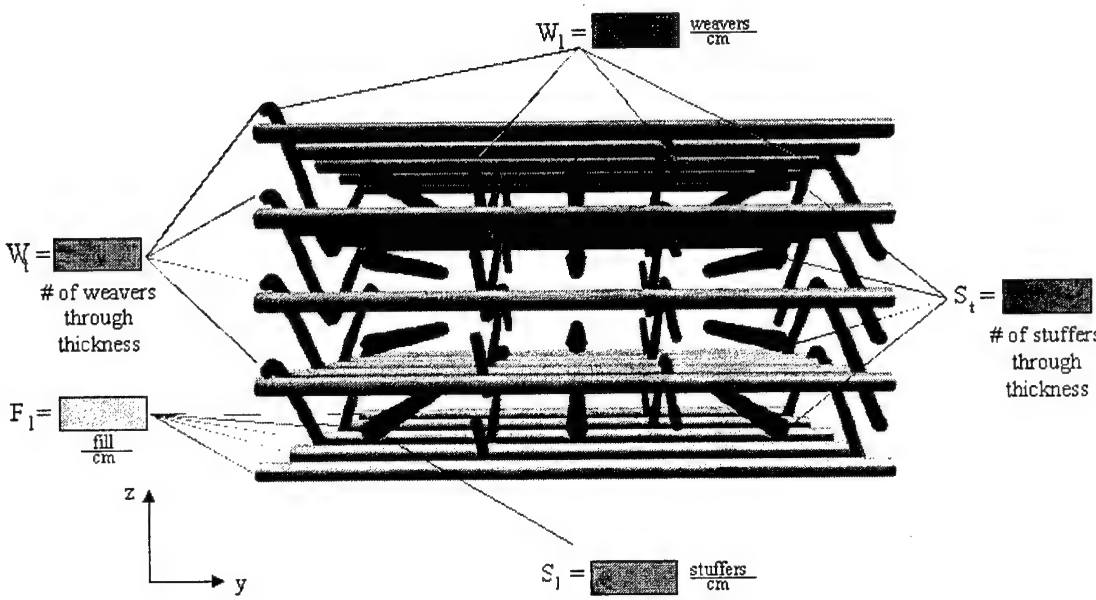

Figure 3: TCSM input window for a layer-to-layer weave.

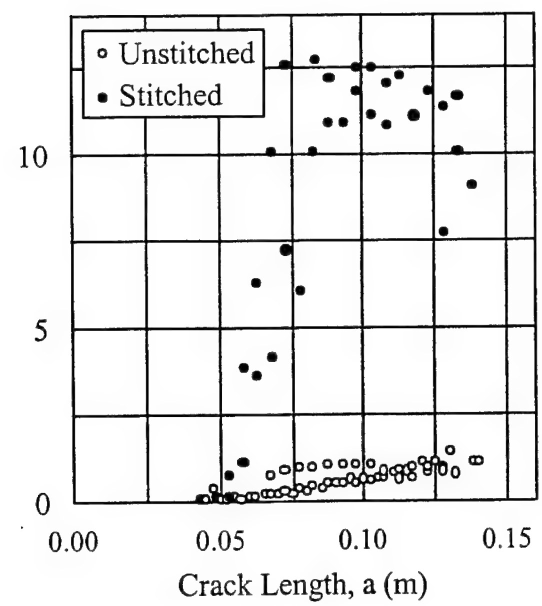

Figure 4: Strain energy release rate vs. crack length for dry roving textile composite.

Input to AFOSR Progress Report – August 2001

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Objectives

The general objective of the research is to study the failure characteristics and the structural behavior/integrity of sandwich composite plates and shells, including buckling strength. The specific objectives of the research done were:

(i) The *growth characteristics of of interface debonds in sandwich beams*, including debond buckling and postbuckling behavior.

(ii) The formulation of accurate solutions for the *buckling strength of sandwich beam/plates.*

Status

We have made satisfactory progress in both items (i) and (ii) above and in understanding the structural behavior of sandwich composites and predicting their integrity and failure characteristics. Specific results of the research are listed in the following section. There is no doubt, however, that further research is needed to fully comprehend the complex phenomena of failure initiation and growth at the face sheet/core interface or inside the core, as well as the interaction of global and local buckling phenomena and their possible detrimental effects on structural integrity of the sandwich structures.

Accomplishments

(1) Buckling and Initial Postbuckling Behavior of Sandwich Beams Including Transverse Shear

An asymptotic solution was formulated for the buckling and initial postbuckling behavior of sandwich beams. The effect of transverse shear was included and the shear correction was calculated from energy equivalency. The asymptotic procedure was based on the nonlinear beam equation (with transverse shear included) and closed form solutions were derived for the critical loads and for the load and mid-point deflection and axial shortening versus applied compressive load during the initial postbuckling phase. Illustrative results were presented for a few typical sandwich construction configurations, in particular with regard to the effect of face sheet and core material system. The simple buckling formula proposed in this work seems to be quite effective in accounting for transverse shear effects.

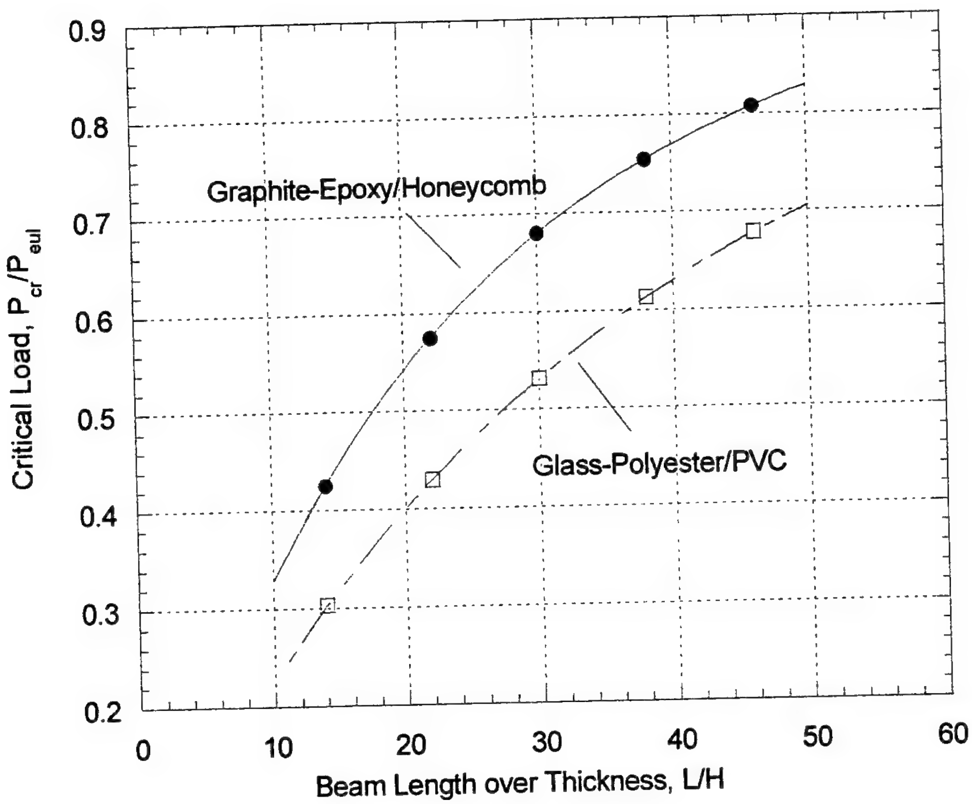

Figure 1. Critical Load, P_{cr}/P_{euler}, versus beam Length over Thickness L/H, for two material sandwich systems. If transverse shear is not included the critical load is the Euler load for both materials. The figure shows the importance of transverse shear in sandwich structures.

(2) Buckling of Sandwich Wide Columns via Numerical and Closed Form Approaches

Research was done on the theoretical prediction of buckling loads for sandwich columns with metallic and laminated facings and honeycomb core. The loading is a uniform axial compression, applied statically (very slowly) and suddenly with constant magnitude and infinite duration (step loading). The effect of length and boundary conditions was assessed and results were presented for the following cases: for a cantilever column, a simply supported column and a clamped column, for several lengths. Several fiber materials are used in the laminated facings. The facings were Boron/Epoxy, Graphite/Epoxy and Kevlar/Epoxy laminates with 0° orientation with respect to the column axis and a metalic one made out of aluminum. These various materials were employed to provide comparative data that can be used in design. Results, for the static case were generated by computer codes as well as by the use of closed form theoretical solutions. For the dynamic case, results are generated by the DYNA3D code. The results show that the Euler load can be larger than the finite element results by a factor of more

than four for some typical column designs, and therefore cannot be relied upon. On the other hand, the formula which we have proposed can be quite effective in predicting a critical load close to the finite element results.

Table 1. Buckling loads of sandwich columns for Alloy-foam core in Newtons. The geomeric values used herein are: c (core height) = 25.3 mm, h (face sheet height)= 2.53 mm, and L(length) = 2032 mm. The width is B = 76.2 mm.

Boundary Conditions	**Source**	**AL 6061-T6**	**Boron/Ep B(4)-5505**	**Graph/Ep T300-5208**	**Kevlar/Ep 49Epoxy**
Cantilever	**Ref. 1**	**3192.05**	**7772.02**	**6618.52**	**3114.49**
	present	**2872.13**	**8183.58**	**6887.44**	**3139.48**
	DYNA3D	**3340.27**	**8230.00**	**6868.60**	**3495.02**
	ABAQUS	**3277.73**	**8086.45**	**6853.00**	**3197.38**
	Euler (Pcl)	**3077.45**	**9850.58**	**8068.18**	**3384.92**
S.S.	**Ref. 1**	**10107.70**	**18946.00**	**17126.90**	**9912.29**
	present	**9880.09**	**24482.50**	**21144.40**	**10692.60**
	DYNA3D	**Not available**	**Not available**	**Not available**	**Not available**
	ABAQUS	**10543.29**	**20215.10**	**18189.46**	**10340.02**
	Euler (Pcl)	**12309.80**	**39402.30**	**32272.70**	**13539.70**
C.C.	**Ref. 1**	**22051.50**	**29576.90**	**28399.60**	**21816.90**
	present	**28715.30**	**61982.10**	**54677.30**	**30695.50**
	DYNA3D	**23700.01**	**25166.65**	**24999.98**	**21066.66**
	ABAQUS	**22863.74**	**37311.03**	**36523.38**	**25291.58**
	Euler (Pcl)	**49239.30**	**157609.00**	**129091.00**	**54158.70**

Ref. 1 is Bazant,Z.P. & Cedolin L., Stability of Structures, Oxford University Press,New York, 1991.

Present is Huang, H. and Kardomateas, G.A. "Buckling and Initial Postbuckling Behavior of Sandwich Beams Including Transverse Shear", submitted to the AIAA J., 2001.

(3) *The Initial Postbuckling and Growth Behavior of Face-Sheet Delaminations in Sandwich Composites –Experiments and Analysis*

Should an interface crack between the layers of the composite face-sheet or between the core and the composite face-sheet of a sandwich beam/plate exists, local buckling and possible subsequently growth of this interface crack (delamination) may occur under compression. Research on this topic was done both analytically and experimentally. On the experimental side, specimens with implaned through-the-width debonds were monotonically compressed and the ensuing debond buckling and growth was recorded. A range of behaviors was observed including self-similar growth and branching of the crack into the core. Data from these experiments are currently being analyzed. On the analytical side, the buckling,and initial postbuckling behavior was studied through a perturbation procedure that is based on the nonlinear beam equations with transverse shear included. Closed form solutions for the load and mid-point delamination deflection versus applied compressive strain during the initial postbuckling phase were derived. Illustrative results were presented for several sandwich construction configurations, in particular with regard to the effect of transverse shear. A comparison with the tests performed is currently being performed.

(4) *Mixed Mode Interface Cracks in Anisotropic Bi-Material Domains.*

This work has resulted in a method for obtaining the mixed-mode stress intensity factors for bi-material interface cracks or cracks parallel to the bi-material interface in half-plane configurations, which are pertinent to face sheet/core configurations.

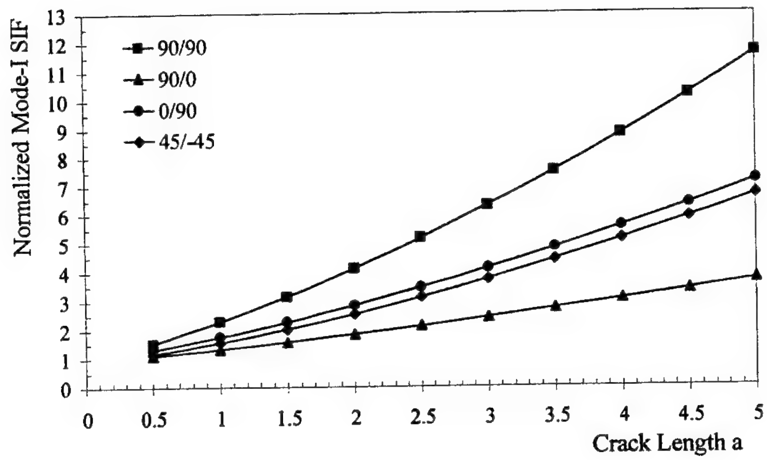

Fig. 2. Mode I SIF for Interface Cracks in a Half Plane

First, dislocation solutions in two different bi-material half planes were presented. The boundaries of these two half planes are either parallel or perpendicular to the bimaterial interface. A surface dislocation model were employed to ensure the traction-free boundary conditions. The dislocation solutions were then applied to calculate the mixed mode stress intensity factors of cracks either at the interface or parallel to the interface. The effects of material mismatch, material interface, and boundary on the stress intensity factors are investigated extensively and show that different material combinations can yield different stress intensity factors for cracks having the same geometries.

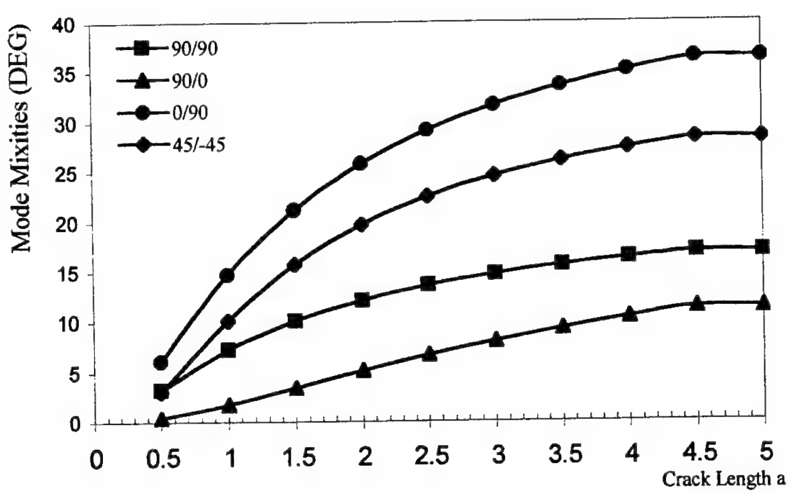

Fig. 3. Mode Mixities of Interface Cracks in a Half Plane

Personnel Supported

George A. Kardomateas, Professor of Aerospace Engineering
Renfu Li, Graduate Research Assistant (partial support)
Valeria La Saponara, Graduate Research Assistant (partial support)
Tianci Jiang, Graduate Research Assistant (since June 2000)

Publications

Journal Papers (Refereed) Published or Accepted for Publication

1. Huang H. and Kardomateas G.A., "Stress Intensity Factors for a Mixed Mode Center Crack in an Anisotropic Strip", International Journal of Fracture, vol. 108, pp. 367-381, 2001.
2. Cho, H. and Kardomateas, G.A., "Thermal Shock due to Heat Convection at a Bounding Surface in a Thick Orthotropic Cylindrical Shell", International Journal of Solids and Structures, vol. 38, pp. 2769-2788, 2001.
3. Kardomateas. G.A., "Effect of Normal Strains in Buckling of Thick Orthotropic Shells", Journal of Aerospace Engineering (ASCE), vol. 13, no. 3, pp. 85-91, 2000.
4. La Saponara, V. and Kardomateas, G.A. "A Statistical Study of Data from Fatigue Tests on Delaminated Cross-Ply Graphite/Epoxy", Journal of Engineering Materials and Technology (ASME), vol. 122, no. 4, pp. 409-419, 2000.
5. Kardomateas G.A. "Elasticity Solutions for a Sandwich Orthotropic Cylindrical Shell Under External Pressure, Internal Pressure and Axial Force", AIAA Journal, Vol. 39, No 4, pp. 713-719, April 2001.
6. Huang H. and Kardomateas, G.A., "Mixed-Mode Stress Intensity Factors for Cracks Located at or Parallel the Interface in Bi-material Half Planes", International Journal of Solids and Structures, vol. 38, pp. 3719-3734, 2001.
7. La Saponara, V. and Kardomateas, G.A. "Crack Branching in Layered Composites: An Experimental Study", in press, Journal of Composite Structures, 2001.
8. Li, R., Frostig, Y. and Kardomateas, G.A., "Nonlinear Response of Imperfect Sandwich Beams With Delaminated Faces Based on Higher Order Core Theory", in press, AIAA Journal, 2000.

9. G.A. Kardomateas, G.J. Simitses, L. Shen and R. Li, "Buckling of Sandwich Wide Columns", in Press, International Journal of Non-Linear Mechanics (Special Issue "On Nonlinear Stability of Structures").

Submitted Journal Papers

1. Kardomateas G.A. and Huang H., "Buckling and Initial Postbuckling Behavior of Sandwich Beams Including Transverse Shear", submitted to the AIAA Journal, 2001.
2. Kardomateas G.A. and Huang H., "The Initial Postbuckling Behavior of Face-Sheet Delaminations in Sandwich Composites", submitted to the Journal of Applied Mechanics (ASME), 2001.
3. La Saponara, V., Hanifah Muliana, Haj-ali, R. and Kardomateas, G.A, "Experimental and Numerical Analysis of Delamination Growth in Double Cantilever Laminated Beams", submitted to the journal of Engineering Fracture Mechanics, 2001.

Conference Presentations

1. Kardomateas G.A. and Huang H., "An Asymptotic Solution for the Response of Face-Sheet Delaminations/Debonds Under Compression", presented at the ME'00, the 2000 International Mechanical Engineering Congress & Exposition, November 5-10, 2000, Orlando, Florida and published in ASME AD-vol. 62/AMD-vol. 245, *Mechanics of Sandwich Structures*, edited by Y.D.S. Rajapakse, G.A. Kardomateas and V. Birman, pp. 133-142, 2000.
2. Kardomateas G.A., "Elasticity Solutions for a Sandwich Orthotropic Cylindrical Shell Under External/Internal Pressure and Axial Load", presented at the ME'00, the 2000 International Mechanical Engineering Congress & Exposition, November 5-10, 2000, Orlando, Florida and published in ASME AD-vol. 62/AMD-vol. 245, *Mechanics of Sandwich Structures*, edited by Y.D.S. Rajapakse, G.A. Kardomateas and V. Birman, pp. 191-200, 2000.
3. Li R., La Saponara V. and Kardomateas G.A., "Nonlinear Behavior of Sandwich Panels with Delaminations inside Face Sheets Based on Refined Higher Order Core Theory", presented at the ME'00, the 2000 International Mechanical Engineering Congress & Exposition, November 5-10, 2000, Orlando, Florida and published in ASME AD-vol. 63, *Proceedings of the ASME Aerospace Division 2000*, edited by J.D. Whitcomb, P. Hajela, A.M. Waas and B.V. Sankar, pp. 93-103, 2000.
4. Kardomateas G.A. and Simitses G.J., "Buckling of Sandwich Wide Columns", 42th AIAA/ASME/ASCE/AHS/ASC SDM Conference, April 16-19, 2001, Seattle, WA, paper no. AIAA-2001-1393.

Interactions

Organized a Symposium on Mechanics of Sandwich Structures at the IMECE'00, the 2000 International Mechanical Engineering Congress and Exposition, November 5-10, 2000, Orlando, Florida, Organized the Symposium together with Dr. Y.D.S. Rajapakse of ONR and V. Birman of U. of Missouri.

Honors

Elected Chairman of the ASME Applied Mechanics Division Composites Committee, effective November 2000.

Contributing Editor, International Journal of Nonlinear Mechanics, since July 2001.

Final Report, Input
by G. J. Simitses

In order to avoid duplication, the tasks treated in collaboration with Drs Victor Birman and George A. Kardomateas will not be reported in this section. The emphasis here is on structural similitude as applied to sandwich configurations.

2. Objective

The objective was to (a) derive the similarity conditions for sandwich structures, (b) use them to design small scale models and (c) use them along with experimental data of the models in order to predict the behavior of the large prototype. In the absence of experimental results for the models, the theoretically obtained response results were treated as experimentally obtained. The predictions were compared to the theoretically obtained response of the prototype.

3. Status of Effort

Similarity conditions for sandwich cylindrical shells under uniform axial compression were derived in a collaborative effort with Drs Birman and Frostig of the Israel Institute of Technology. Two publications resulted from this effort and were included in Dr Birman's report. This effort was followed by applying similitude theory to sandwich beams. This effort was incollaboration with Dr Frostig. Similarity conditions (scaling laws) were derived for sandwich beams in bending (transversely loaded) by employing the symbolic algebraic interpreter software MAPLE. These conditions were used to design the small scale model, which model was analyzed by employing a high-order bending theory. The analytical results of the model were then treated as experimentally obtained and by employing the scaling laws, the behavior of the prototype was predicted. These predictions were compared to the theoretically obtained response of the prototype. The comparison was excellent, which demonstrated successfully the developed methodology.

4. Accomplishments and New Findings

It was successfully demonstrated that structural similitude theory can be applied to sandwich structures in order to predict the behavior of large prototypes through the use of scaled down models, which are inexpensive and easily tested in a laboratory.

5. Personnel Supported

Research was conducted by G. J. Simitses in collaboration with Mr. Liang Shen, graduate assistant and Mr. G. Song, M. S. student. Both attending the University of Cincinnati. In addition, Drs Birman and Frostig served as research collaborators.

6. Publications 1998-Present

See list provided by Drs V. Birman and G. A. Kardomateas. In addition,

1. Y. Frostig and G. J. Simitses "Structural Beams" AIAA Paper 2001-1280; accepted by AIAA J. for publication. It will appear in 2002.

Other Publications During Contract Period

1. G. J. Simitses and A. Tabiei "Dynamic Stability of Plates and Shells" in Stability Analysis of Plates and Shells, NASA/CP 1998-206280, Hampton, VA, 1998, pp.285-292.

2. A. Tabiei and G. J. Simitses, "Scaled Down, Imperfection Sensitive, Composite, Cylindrical Shells Under Axial Compression and Lateral Pressure" in Stability Analysis of Plates and Shells, NASA/CP 1998-206280, Hampton, VA, 1998, pp. 362-367.

3. B.K. Walker, S-M Jeng, P.D. Orkwis, G.L. Slater, P.K. Khosla & G.J. Simitses, "Redesigning an Aerospace Engineering Curriculum for the Twenty-First Century Results of a Survey," J. of Engineering Education, ASEE, Vol. 87, No. 4, 1998, pp. 481-489.

4. G.J. Simitses and S. S. Hsiung, "Imperfection Sensitivity of Moderately Thick Laminated Cylindrical Shells" ASCE J. of the Aerospace Engineering, Vol. 12, No. 1, 1999, pp. 8-14.

5. A. Tabiei, R. Tanov and G. J. Simitses, "Numerical Simulations of Cylindrical Laminated Shells Under Impulsive Lateral Pressure" AIAA J., Vol. 37, No. 5, 1999, pp. 629-633.

6. Tanov, A. Tabiei and G.J. Simitses, "Effect of Static Preloading on the Dynamic Buckling of Laminated Cylinders Under Sudden Pressure" Mechanics of Composite Materials and Structures, Vol. 6, No. 3, 1999, pp. 195-206.

7. G.J. Simitses, J.H. Starnes, Jr. and J. Rezaeepazhand, "Structural Similitude and Scaling Laws for Plates and Shells: A Review" in Advances in the Mechanics of Plates & Shells, The A. Libai Anniversary Volume, edited by D. Durbam, D. Giuoli and J.G. Simmonds, Elviver-Academic Publishers, 2001, pp. 295-310.

8. Interaction/Transitions

a. Participation in Conferences
   See lists provided by Drs V. Birman and G. A. Kardomateas
b. Consulting served as evaluator of
   (1.) Aerospace Engineering Program at the U. of Patras, Greece, December

1999, and
(2.) Graduate Program in Structural Mechanics at the National Technical University of Athens (Greece), June, 2000.

9. New Discoveries: None

10. Honors & Awards

a.) Served in several societal committees
b.) Served on the Editorial Boards of Three Journal (composites Part B: Engineering, Int'l J. of Non-Linear Mechanics and ASME Applied Mechanics Reviews).
c.) Chaired several sessions at professional meetings.
d.) Was elected Fellow of AIAA and American Academy of Mechanics
e.) Was elected Honorary Member of the Hellenic Society of Theoretical and Applied Mechanics
f.) Was elected Corresponding Member of the Academy of Athens (Greece).
g.) Was listed in many Who's Who lists.

Studies of Structural-Acoustic Problems of Advanced Sandwich Structures for Global Transport

This part of the research within the project of New World Vista consists of two parts. The first part deals with the sound transmission studies across sandwich panels, while the second develops mathematical models and computational methods for studying the structural-acoustic problem of non-circular sandwich shell, which is perceived to be the geometry of the future global transport aircraft.

The studies of this research are mostly analytical and numerical. Experimental validation of many interesting results obtained in the course of the research needs to be done in the future. Most research results have been published in refereed journal and presented in professional meetings. A doctoral student supported by the project has finished a dissertation in June 2001. A complete list of all publications is attached at the end of this writing. In the following, we shall highlight some achievements of the research.

Optimization of Sandwich Construction for Minimum Sound Transmission

We have studied the vibration and sound transmission across sandwich panels made of anisotropic materials. The displacements of the core of the sandwich are assumed to be functions of cubic polynomials of the thickness coordinates leading to the so-called higher order modeling of the sandwich. We have found that anisotropy of the material can provide significant improvement of the vibration and sound isolation performance of sandwich structures. This study has opened new research opportunities of optimization of sandwich structures for better vibration and sound isolation.

Following the analysis, we then proceed to study the optimization problem of the sandwich panels for minimum sound transmission. We have chosen the materials properties including mass density and shear-to-normal coupling material constants and the geometrical parameters including the thickness of each layer as the design parameters. Extensive numerical studies of optimization have been conducted. We have found, for example, that when the total thickness of the panel is constrained to be constant and the static strength of the panels is fixed, the optimized panel tends to have a thinner skin toward the sound source than that of the skin away the source. There is no clear and simple physical explanation of this interesting result at this time. However, the result is intriguing enough to require us conduct further studies along this line in the future.

Modeling and Structural-Acoustic Analysis of Non-Circular Sandwich Shells

We have also developed methodologies for analyzing the vibration and interior sound response of cylindrical sandwich shells with non-circular cross section. This shell was proposed by Professor Vinson, the PI of the project, to be the candidate geometry of the future global transport. We have developed a mixed symbolic and numerical computational approach to obtain dynamic solutions of the structural-acoustic system.

We have used a conformal mapping approach to transform the non-circular domain in to a unit circle. The mode functions of a uniform circular cylindrical shell provide a set of orthogonal comparison functions for the non-circular shell. Ritz method is used in the circular domain to derive equations of motion. This mapping technique is applicable to both the structural and acoustic problems.

The mathematical modeling and the computational method developed here provide a solid platform for dynamic analysis and design of the future global transport. Such a utility of the present study has not been fully explored at this time, and should be done in the future projects.

In the study, we have developed a computational method for analyzing fully coupled structural-acoustic system by using a so-called particular solution approach. This method overcomes the common shortcoming of many methods in the literature and exactly satisfies the structural-acoustic interface boundary condition.

List of Publications by J. Q. Sun and his Student

[1] Sun, J. Q., 1999, "An Impedance Study of Curved Sandwich Trim Panels Driven by Piezoelectric Patch Actuators," Journal of Sandwich Structures and Materials, **1**, pp. 128-146.

[2] Thamburaj, P. and Sun, J. Q., 1999, "Effect of Material Anisotropy on the Sound and Vibration Transmission Loss of Sandwich Aircraft Structures," Journal of Sandwich Structures and Materials, **1**, pp. 76-92.

[3] Thamburaj, P. and Sun, J. Q., 2000, "Modal Analysis of Fully Coupled Structural-Acoustic Systems," Journal of Sound and Vibration, **In review**.

[4] Thamburaj, P. and Sun, J. Q., 2001, "Modal Analysis of a Non-Circular Cylindrical Laminated Shell Using Conformal Mapping," Journal of Sandwich Structures and Materials, **3**, pp. 50-74.

[5] Thamburaj, P. and Sun, J. Q., 2001, "Acoustic Response of a Non-Circular Cylindrical Enclosure Using Conformal Mapping," Journal of Sound and Vibration, **241**, pp. 283-295.

[6] Thamburaj, P. and Sun, J. Q., 2001, "Effect of Material and Geometry on the Sound and Vibration Transmission across a Sandwich Beam," Journal of Vibration and Acoustics, **123**, pp. 205-212.

[7] Thamburaj, P. and Sun, J. Q., 2001, "Optimization of Anisotropic Sandwich Beams for Higher Sound Transmission Loss," Journal of Sound and Vibration, **In review**.

[8] Thamburaj, P., 2001, "Structural-Acoustic Studies of Sandwich Structures for Global Transport Aircraft," Ph.D. Dissertation, University of Delaware.

[9] Sun, J. Q., 1999, "Active Sandwich Trim Panels for Quieter Aircraft Interior," *Proceedings of ASME IMECE-99*, ASME, Nashville, Tennessee.

[10] Thamburaj, P. and Sun, J. Q., 1998, "Recent Studies of Sound Transmission Loss of Sandwich Aircraft Structures," *Proceedings of ASME International Congress and Exposition*, Anaheim, California.

[11] Thamburaj, P. and Sun, J. Q., 1999, "Noise and Vibration Isolation across Sandwich Structures," *Proceedings of the SPIE Smart Structures and Materials'99*, Newport Beach, California.

[12] Thamburaj, P. and Sun, J. Q., 2000, "Vibrations of a Non-Circular Cylindrical Shell Using Conformal Mapping," *Proceedings of the 8th Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures*, Virginia Tech, Blacksburg, Virginia.

AFOSR – PROGRESS REPORT – REVISED

"ADVANCED COMPOSITE MATERIAL RESEARCH FOR THE NEW WORLD VISTAS"

Ole Thybo Thomsen, Professor, Ph.D.
Institute of Mechanical Engineering, Aalborg University, Denmark

On sabbatical leave with the
Department of Mechanical Engineering, University of Delaware
September 1999 – August 2000

I. Basic Research: Development of High-Order Sandwich Theory Formulations for the Analysis of Straight, Tapered and Curved Sandwich Panels

Structural sandwich panels can be considered as a special type of composite laminate where two (or more) thin, stiff, strong and relatively dense faces (which may themselves be composite laminates) are separated by a thick, lightweight and compliant core material. Such sandwich panels have gained widespread acceptance as an excellent way to obtain extremely lightweight components and structures with very high bending stiffness, high strength and high buckling resistance.

Despite the above advantages it is well known that sandwich structures are notoriously sensitive to failure by application of concentrated loads, at points or lines of support, and due to localized bending effects induced in the vicinity of points of geometric and material discontinuities. The reason for this is that although sandwich structures are well suited for the transfer of overall bending and shearing loads, localized shearing and bending effects, as mentioned above, induce severe through-thickness shear and normal stresses. These through-thickness stress components can be of significant magnitude, and may in many cases approach or exceed the allowable stresses in the core material as well as in the interfaces between the core and the face sheets.

In order to accommodate for the above in the evaluation of the structural integrity of sandwich panels it is necessary to possess analysis tools that are capable of quantifying the stress state in the core material, as well as capable of quantifying the interaction between the faces through the core. This can be achieved in various ways, and during the sabbatical stay of Dr. Thomsen with the Department of Mechanical Engineering at the University of Delaware a special high-order sandwich theory formulation has been developed. In the developed high-order sandwich theory formulation the elastic response of each face laminate is accounted for, including bending-stretching coupling and transverse shear deformations, and the transverse flexibility of the core is included. Thus, the faces are allowed to deflect differently, and the sandwich panel thickness may change during deformation. Also, the theory accounts for the existence of transverse normal and shear stresses in the core material. The high-order theory approach has been developed and implemented for the following structural sandwich panel assemblies:

- General multi-layer sandwich plate assemblies involving N stiff "face" layers separated by N-1 compliant "core/interface" layers, Refs. [1], [2].

- 3-layer sandwich panel assemblies including the following:
  - Straight sandwich panels with parallel faces, Refs. [3], [4], [5], [6].
  - Tapered sandwich panels with variable core thickness, and non-parallel faces of constant thickness, Refs. [4], [6].
  - Constant curvature sandwich panels, Refs. [3], [4], [5], [6].

The high-order sandwich theory models was further explored and developed for the purposes of Refs. [9], [10] presented at the 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Seattle, WA, 16-19 April 2001, and submitted for the AIAA Journal.

II. Applied Research: Analysis and Design of Non-Circular Composite Sandwich Fuselage Cross Sections Subjected to Internal Pressure Loading

The developed analysis and design tools have been applied for conduction of a series of numeric and parametric studies regarding the mechanical response of non-circular composite sandwich fuselage cross sections subjected to internal pressure loading.

The numerical studies have involved constant and variable thickness fuselage cross sections, and the following primary findings can be highlighted, refs. [3], [4], [5], [6]:

- Significant global bending and shearing effects are induced in the fuselage cross section plane, and this may cause the inducement of significant stress concentrations in the faces and in the core material.
- Localized bending effects are unavoidable in the vicinity of locations where the sandwich panel geometry and material properties change.
- The stress concentrations induced by "global" bending and shearing can be alleviated, and the global stiffness of the non-circular fuselage can be increased, without compromising the overall weight, by adopting a variable thickness design.
- The beneficial effects with respect to the "globally induced" stress concentrations that can be obtained by adopting a variable thickness fuselage design, may be counteracted by the inducement of severe localized bending and core stresses in the vicinity of the locations where the sandwich panel geometry changes abruptly.

The conducted parametric studies have investigated the effects of varying the following different geometric and material properties, Refs. [3], [5]:

- Sandwich panel mid-plane asymmetry.
- Stiffness properties of face and core materials.
- Core thickness.
- Radius of rounded corners of non-circular sandwich fuselage.

III. Other Research Activities

During the report period Dr. Thomsen has been actively involved in other research activities than the above mentioned. These additional research activities includes development and implementation of newly developed methods for analysis and design of adhesive bonded joints, Ref. [7], manufacturing and through-thickness characterization of stitched and z-pinned thick CFRP laminates, Ref. [8], and an

experimental and analytical study on the behavior of foam core sandwich plates subjected to in-plane shear loading, Ref. [11]. The latter is directly related to the research activities described under points I and II above.

IV. Honors/Awards

Dr. Thomsen was given the 1999 Best Paper Award by the Polymer Matrix Composites Division under the American Society for Composites (ASC) for his paper "High-order Plate Formulation for the Modeling of Multiple Layer Sandwich Type Structures" given at the Annual ASC Technical Conference, Dayton, OH, September 1999.

As of 1 April 2001 Dr. Thomsen was promoted to full professor in the fields of "solid mechanics" and "mechanics of lightweight structures" with the Institute of Mechanical Engineering, Aalborg University, Denmark.

V. Publications

<u>Scientific articles – completed:</u>

[1] Thomsen, O.T., 2000. "High-Order Theory for the Analysis of Multi-Layer Plate Assemblies and its Application for the Analysis of Sandwich Panels with Terminating Plies", *Composite Structures*, Vol. 50, No. 3, pp. 227-238.

[2] Thomsen, O.T., 2000. "Modeling of Multi-Layer Sandwich Type Structures Using a High-Order Plate Formulation", *Journal of Sandwich Structures and Materials*, Vol. 2, No. 4, pp. 331-349.

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Final Report on Research performed by Dr. Jack R. Vinson and his Students Regarding the

Global Range Transport Fuselage

During this four year period, the research performed by Dr, Vinson and his students has concentrated on two areas:

1. The use of mid-plane asymmetry, which causes bending stretching coupling in structural components, to reduce the structural weight to perform the same functions of more traditional structures
2. The study of the fuselage structure itself, both in a two dimensional configuration, in which plane strain is assumed in the axial direction, and the entire shell structure itself.

In all cases, methods of analysis are developed in order for the deformations and stresses in that structure be determined, but also methods of structural optimization have been developed in order that the best materials can be selected and the dimensions determined in order to attain the minimum weight for the given loads.

Mid-plane asymmetry makes sense because in some materials there are differing strengths in tension and compression; in structures in which the external face is at a significantly different temperature than the other face, the material properties differ even though the material is the same; and there are many cases with both laminated and sandwich constructions inb which one wishes to use different materials for the inner and the outer faces because of differing chemical or esthetic reasons.

Beginning with a paper co-authored with A.T. Dee [1], a mid-plane asymmetry factor was introduced by which the mid-plane asymmetry of a laminated or sandwich structure can be described easily. This factor, dubbed phi, is zero for the conventional structural architectures, and is always less than unity for any asymmetric laminate or sandwich construction.

Because this is a small parameter, it lends itself to perturbation series solutions for some problems, wherin the mid-plane symmetric solutions are perturbed about the symmetric condition. It was found that never more than two terms of the series are necessary to obtain good solutions.

A series of papers by Satapathy and Vinson [2-5], developed methods of analysis and structural optimization for mid-plane asymmetric sandwich beams under lateral loads.

The research associated with these papers and the study of plates of mid-plane asymmetric construction comprised the master's thesis of Satapathy [6].

The study of a two dimensional cross-section of the boxy rectangular fuselage with rounded corners was studied with an internal pressure, wherein plane strain was assumed in the axial direction. This is a reasonable assumption for most of the fuselage outside the bending boundary layer near the ends of the shell structure. Forbes [7] developed solutions for this configuration and conducted studies to obtain minimum weight and identify the best materials for this construction. At the same time Thomsen, on sabbatical leave at Delaware used a high order sandwich theory to study the same problems, Only through corroboration between the two solutions, done by different people and different methods, can confidence be given to the methods and results obtained using either method for this very complicated, never before studied problem. The papers resulting from the collaboration with Thomsen are given in his section and will not be repeated here. It is found that under internal pressure the boxy fuselage deforms in a way that it is trying to become a circular cylinder as expected. That means that in the middle of the flat sides, the outer sandwich faces are in tension and the inner faces in compression. In the rounded corners just the opposite occurs. The rounded corners are bent in such a way as if they are tryin to straighten out, thus putting the outer sandwich faces in compression and the inner faces in tension..

With this behavior, in some cases, because the bending moments change sign between the straight and curved portions, and are of abpout the same magnitude, one might conclude that mid-plane asymmetry accomplishes very little. However that is for the case of constant thickness faces and core depth

everywhere. However, with modern methods of manufacture in which one can vary face thickness and core depth, the judicious use of mid-plane asymmetry can produce a superior weight reduced structure compared to the more conventional constant thickness construction.

Concurrent with these pursuits, Chen and Preissner studied these problems as well as attacked the problem of the three dimensional shell fuselage under internal pressure for their doctoral dissertations. Neither has completed this task. Preissner finds that even in this boxy configuration involving plate elements and corner shell elements, there still exists a bending boundary layer in the shell

Aimmanee [8] developed methods of analysis and optimization techniques for panels composed of foam reinforced web core sandwich construction (or web reinforced foam core sandwich construction) References subjected to in-plane compressive loads to see if it had merit for the Global Range Transport fuselage. He found that at low load index loads that foam core sandwich constructipn alone was superior. At high load index loads the web core construction alone was superior. However there is an intermediate range of load indices in which the constructions described above has merit

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